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ASPECTS OF THE SEDIMENTOLOGY, ICHNOLOGY, STRATIGRAPHY, AND RESERVOIR CHARACTER OF THE MCMURRAY FORMATION, NORTH-EAST ALBERTA

©

BY

CHAD ROSS EDWARD HARRIS

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DEPARTMENT OF EARTH AND ATMOSPHERIC SCIENCES

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Dr. S. George Pemberton - Supervisor

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Date: January 31, 2003

ABSTRACT

The McMurray Formation in the surface-mineable Athabasca Oil Sands was studied in order to better define the strata surrounding the Ells River and develop a facies scheme that effectively links seven outcrops and forty nearby core sections into cohesive facies associations. Incorporation of sedimentological, ichnological, and stratigraphic analysis suggest initial deposition during the Lower Cretaceous was fluvially controlled evolving into a complex estuarine fill. Ichnological analysis confirmed the presence of brackish water conditions during the bulk of McMurray deposition with an increase in the biological carrying capacity of the environment up-section.

The presence of an oil-water contact exposed in outcrop along the Steepbank River allowed analysis of the relationship between the high-viscosity oil and formation water that can be extrapolated into the subsurface. The contact undulates up to five vertical meters over a forty meter lateral interval. This has implications to reservoir evaluation and well placement for in-situ recovery techniques such as Steam Assisted Gravity Drainage (SAGD).

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CHAPTER 1 - INTRODUCTION

INTRODUCTION

In northeastern Alberta the McMurray Formation is a succession of early Cretaceous sediments belonging to the Mannville Group. The McMurray Formation is the predominant stratigraphic unit associated with the Athabasca Oil Sands deposit, containing over 200 billion cubic meters (1.3 trillion barrels) of bitumen in place (ERCB, 1990)(Table 1.1). The McMurray Formation and the Wabiskaw Member of the Clearwater Formation contain the major portion of in-situ bitumen with 142 billion cubic meters or 893 billion barrels (ERCB, 1990). This compares with just over 300 million cubic meters of conventional reserves catalogued in 1999 (AEUB, 2000). The deposit thins and pinches out on the Canadian Shield to the east and the Grosmont High (Wainwright Ridge) to the west (Stewart, 1963). To the northwest the McMurray sands grade into marine shales while to the north and northeast, the extent of the oil sands has been limited by glacial erosion (Stewart, 1963;

Area	Deposit	Areal extent (10^3ha)	Mean pay (m)	Bitumen in place (10^9m^3)	Bitumen in place (10^9bbl)
Athabasca	Grand Rapids	689	7	7	44
	McMurray / Wabiskaw	4642	35	142	894
	Grosmont / Nisku	4666	10	61	384
				210	1322
Cold Lake	Grand Rapids	1640	6	20	126
	Clearwater	589	15	11	69
	McMurray / Wabiskaw	670	6	4	25
				35	220
Peace River	Bluesky / Gething	1000	11	11	69
	Debolt / Shunda	445	19	10	63
				21	132

Table 1.1. The distribution of hydrocarbons in the oil sand deposits of Alberta (from ERCB, 1990).

Fig. 1.1. The distribution of major Lower Cretaceous oil sand deposits in Alberta. The surface mineable portion of the Athabasca Oil Sands deposit is highlited darker (modified from Hubbard *et al.*, 1999).

Ranger, 1994). The southern limit of the deposit is poorly defined.

The oil contained within the oil sands is relatively heavy, characterized by American Petroleum Institute (API) gravities of between 7° and 10° (Rennie, 1987). Normal light oils for comparison have API gravities of 35-40° (Selley, 1985) and can be recovered effectively with conventional techniques. Due to the high viscosity of the oil within the oil sands, the deposit requires specialized recovery techniques. The deposit can be separated into surface mineable areas and areas that are too deep to surface mine and therefore require in-situ recovery methods (Figure 1.1). Surface mining is currently taking place north of Fort McMurray at operations run by Syncrude Canada Ltd., and Suncor Energy Ltd., while Shell Canada Ltd., TrueNorth Energy Ltd., and Canadian Natural Resources

Ltd. are all in the process of developing mines at nearby locations (Figure 1.2). These and other corporations have recognized the significance of this resource and the success of the established operations. In-situ operations have been tested at various locations with varying success rates. A clear understanding of the character, geometry, and internal variations within the reservoir are key to maximizing production in either a mining or in-situ development application.

In-situ methods involve heating the heavy oil/bitumen to a less viscous state so that it can flow freely (Towson, 1977; Newell, 1999). Steam injection has proven to be the most effective method of heating the bitumen (Butler, 1998). Two of the competing steam injection methods are steam stimulation and steam drive. Steam stimulation is a technique in which production is accomplished with one well. The injection/production well in this arrangement injects steam into the formation, and after a shut-in period, produces the migrated bitumen. This methodology has proven very successful at the Cold Lake properties of Imperial Oil (Stancliffe and van der Kooij, 2001) where production is obtained from the Clearwater Formation. Effective steam drive involves a minimum of two wells, a dedicated injector and a dedicated producer, that are arranged in a certain pattern to maximize oil recovery (Butler, 1998). The injected steam provides the driving force in both applications.

Bitumen grade, defined by mass bitumen versus mass water, is largely determined by lithology within the McMurray Formation (Carrigy, 1962; Wightman and Pemberton, 1997; Hein *et al.*, 2000). Well-sorted sands with few clays and high porosity and permeability have the highest degree of bitumen saturation (Harris *et al.*, 1999; 2000; Hein *et al.*, 2000). Mossop (1980) concluded that since the McMurray Formation sediments have undergone little to no post-depositional modification (quartz diagenesis, clay authigenesis, etc.), the distribution of bitumen content is dependant on facies distribution. Local post depositional cementation has occurred in McMurray sediments as shown by the tightly cemented intervals related to the presence of Devonian sinkholes and related fault zones in

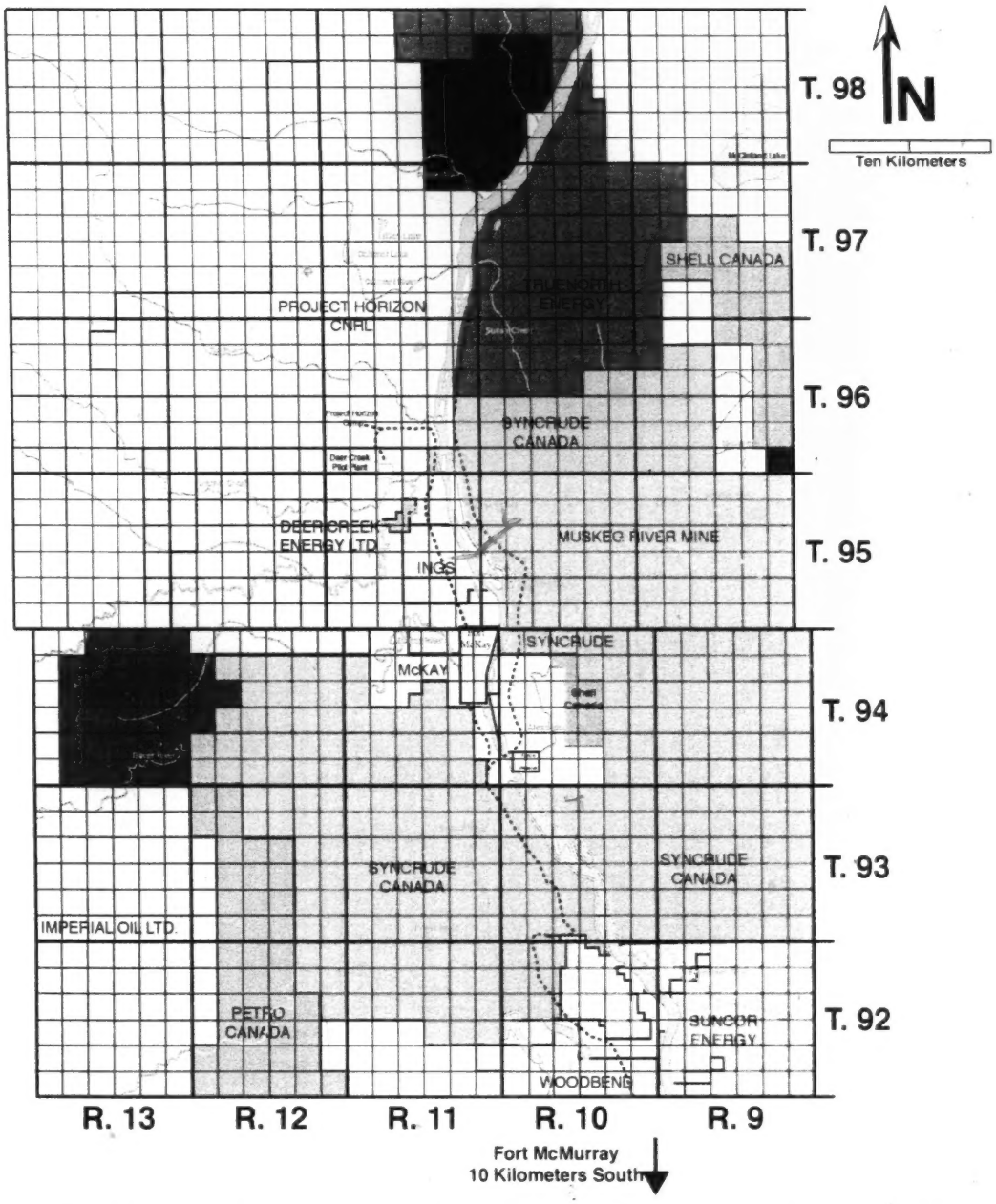


Fig. 1.2. Suncor Energy Ltd. currently operates oil sand surface mines located in T.92, R.8 and T.92, R.10. Syncrude Canada Ltd. operates surface mines located in T.92, R.11 and T.96, R.10. Shell Canada Ltd., TrueNorth Energy Ltd., and Canadian Natural Resources Ltd. are all in various phases of oil sand mine development.

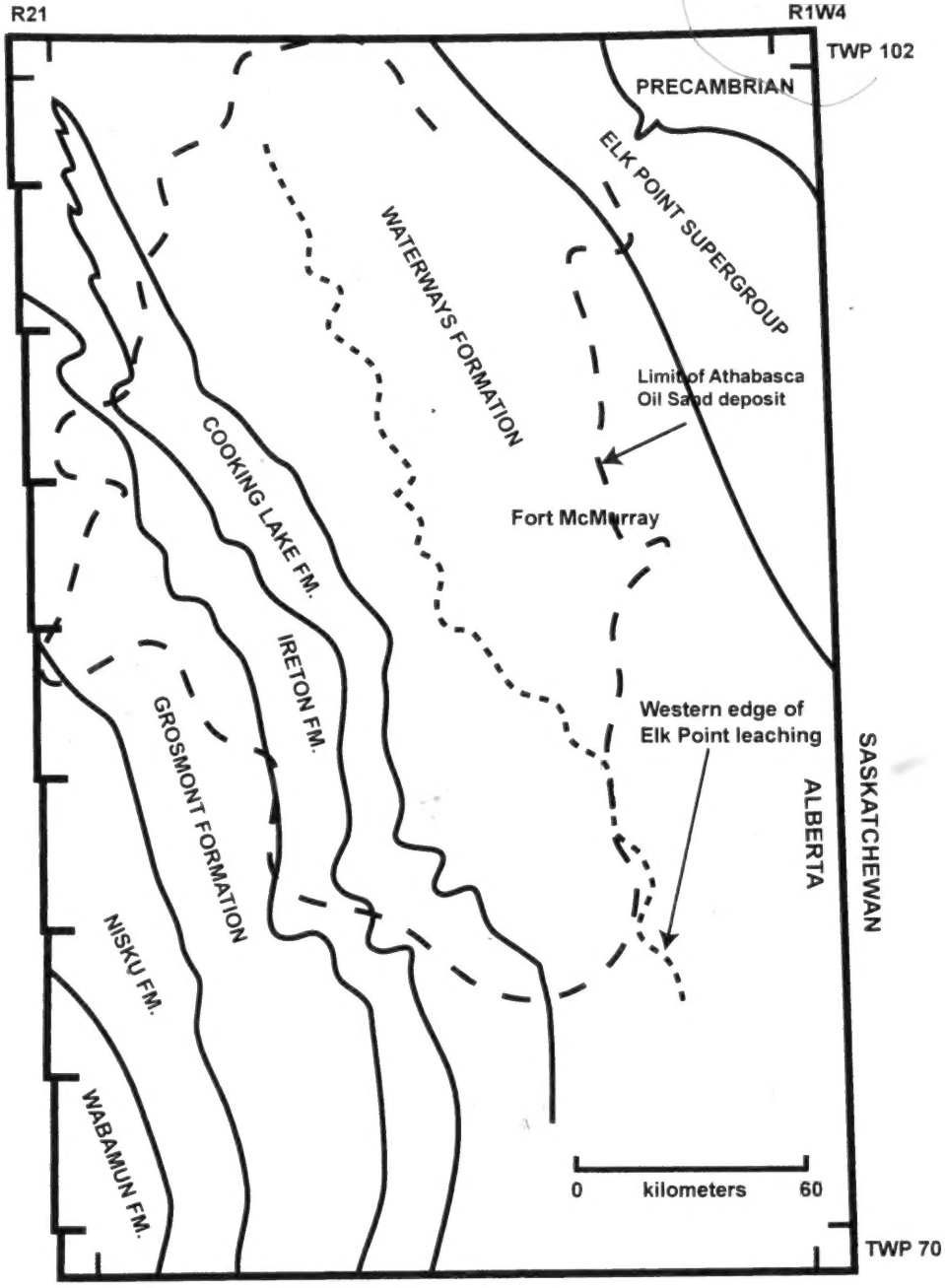


Fig. 1.3. Regional subcrop map of Devonian strata at the pre-Cretaceous unconformity (modified from Stewart, 1963; Norris, 1973).

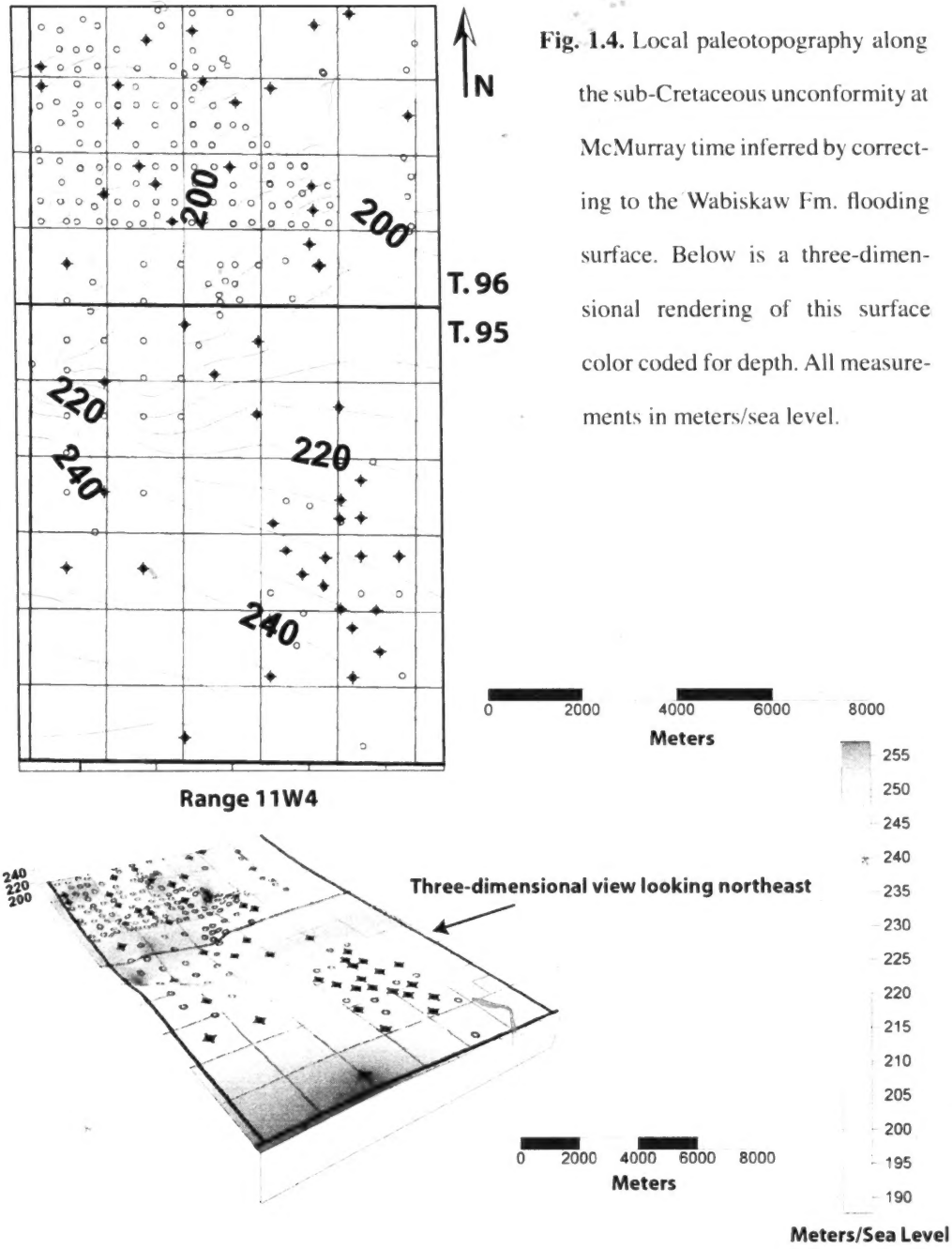


Fig. 1.4. Local paleotopography along the sub-Cretaceous unconformity at McMurray time inferred by correcting to the Wabiskaw Fm. flooding surface. Below is a three-dimensional rendering of this surface color coded for depth. All measurements in meters/sea level.

the current Ells River study area (Figures 1.3 and 1.4).

Detailed description and interpretation of the sedimentology of the McMurray Formation from core and outcrop studies will lead to a better overall understanding of the physical processes responsible for facies distribution in the McMurray Formation (Bechtel, 1996; Wightman and Pemberton, 1997). Physical structures represent physical processes occurring in the depositional environment due to their creation in particular depositional energies. Fluid flow over cohesion-less sediments produces recognizable and predictable sedimentary bedforms. Since a sedimentary environment is a process-response system, variations in the hydrodynamic conditions should be imparted onto the sedimentary record (Allen, 1963). Combining the use of ichnology (the study of the behavior of organisms that affect the substrates in which they may be found) with physical sedimentology is integral to formulating depositional environment interpretations. Trace fossils are the result of organisms burrowing and/or modifying the sediment (Bromley, 1990). The use of ichnology in previous studies of the McMurray Formation (Pemberton *et al.* 1982; Ranger and Pemberton, 1992; Ranger; 1994; Bechtel, 1996; Wightman and Pemberton, 1997) has greatly contributed to the interpretation of the depositional environment.

Knowledge of the lateral and vertical continuity of the sand bodies contained in the McMurray Formation is fundamental to understanding the deposit. The preservation of facies in the study area is crucial to understanding the lateral facies variations. Lateral variability in the McMurray Formation has been previously described by Kendall (1977), Mossop (1980), Rennie (1987), Ranger (1994), Bechtel (1996), and Hein *et al.*, (2000). A better understanding of the lateral facies associations is best achieved by grouping vertical successions of gradationally connected facies into facies associations, a technique superior to simple grouping done on a lithostratigraphic basis (Galloway and Hobday, 1996). Bounding surfaces between these genetically related facies are key to the development of a facies model which can serve as a tool for predicting lateral and vertical facies relationships. Understanding the resultant effects on bounding surfaces where eustatic sea-

level changes are imparted on a depositional environment can lead to the development of a sequence stratigraphic model. Interpreting these bounding discontinuities from both the sedimentology and ichnology will contribute to a clearer overall comprehension of the McMurray Formation.

Knowledge of the extent of thick, bitumen-rich sand bodies in the McMurray Formation and understanding the controls that affect the distribution of oil-saturated and water-saturated sands is necessary for in-situ recovery techniques. The highest bitumen saturation levels occur immediately above the oil-water contact in clean sands (Mossop, 1980; Wightman and Pemberton, 1997). It is also important to ascertain whether the sand bodies contain any thick muds that may hinder or help production by dividing the sand body into smaller reservoirs (Kendall, 1977). A competent interpretation of an environment of deposition would aid in delineating these sand bodies and their internal consistencies and form a predictive tool for lithology and in turn bitumen saturation.

The objectives of this study are to: 1) identify (using sedimentology and ichnology) and catalogue a limited set of facies which can be used to elucidate the nature of the depositional system and its effects on facies distribution and continuity within the McMurray Formation in the Ells River area; and 2) determine if facies distribution has an effect on the preserved paleo- oil-water contact expressed in outcrop along the Steepbank River. The importance of facies groupings related to bounding surfaces is expressed in the use of facies associations in this study to address paleo-environmental interpretation issues. The bounding surfaces themselves will be addressed between facies with the end result being a genetic stratigraphic interpretation of the deposits in the area of the Ells River.

STUDY AREA

This is a detailed local study of several outcrops along the Ells and Steepbank Rivers combined with a subsurface study in the north Athabasca region. The study area is located in the surface-mineable portion of the Athabasca Oil Sands. It covers four distinct oil sand leases as defined by the Alberta Energy and Utilities Board (1998). The outcrops studied along the Ells River are in a small lease owned by Shell Canada Ltd. designated as oil sand lease 15 (OSL 15). The subsurface study of core from nearby wells crosses oil sands leases 6 and 7 (OSL 6, OSL 7) in the south of Township 95 belonging to Canadian Natural Resources Ltd. as well as oil sand lease 24 (OSL 24) belonging to Deer Creek Energy Ltd. in the rest of Township 95 and the southern portion of Township 96. The northern end of the study area is in oil sand lease 18 (OSL 18) owned by Canadian Natural Resources Ltd. (Figure 1.5). The Steepbank River sections are located in oil sand leases 11 and 25 (OSL 11, OSL 25) currently part of the Steepbank Mine Expansion of Suncor Energy Ltd (Figure 1.5).

The Steepbank River is located 20 kilometers north of the town of Fort McMurray in Township 92 and Ranges 9W4 and 10W4 (Figure 1.5). The Ells River and subsurface study area are located approximately 45 kilometers north of Fort McMurray and borders the First Nations Reserve of the McKay Band in Range 11W4 and Townships 95 and 96 (Figure 1.5). Several outcrops along each river were identified both visually and using the outcrop atlas of Ells (1926) and Flach (1984). The best outcrops, defined by exposure, location, and vertical/horizontal continuity were described in detail and logged using a portable gamma ray spectrometer.

Overburden in this area typically comprises later Cretaceous sediments and Holocene glacial deposits that can range in thickness from 5 to 45 meters. The sediments preserved beneath the study area are Devonian carbonates comprising the Moberly Member of the Waterways Formation in the Beaverhill Lake Group, and the Cretaceous McMurray Formation and overlying Clearwater Formation of the Mannville Group. Neither the Clearwa-

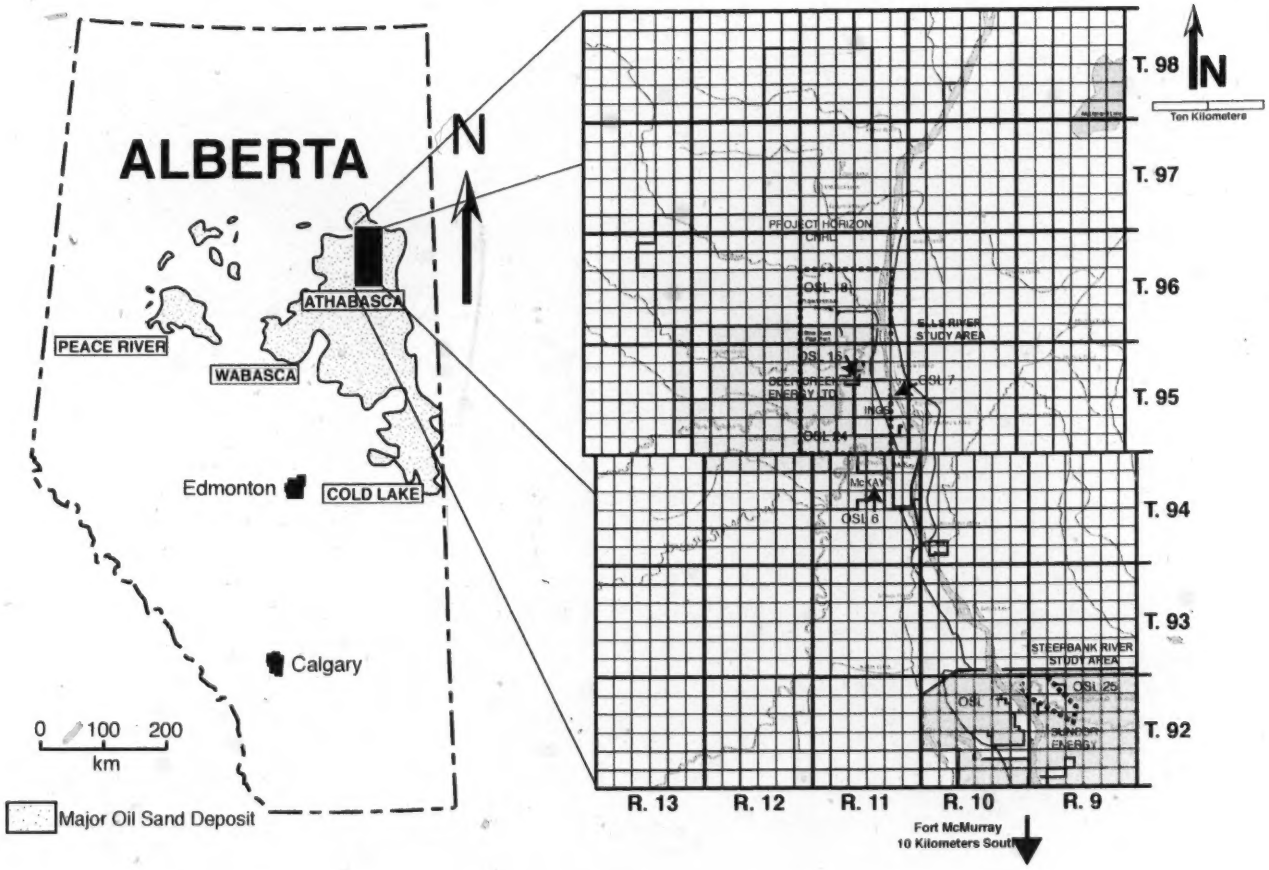


Fig. 1.5. The study is focused in two distinct areas, the Steepbank River Study Area (South) and Ells River Study Area (North).

ter Formation nor Devonian sediments were encountered in the outcrops along the Ells River although they were prominent features along the Steepbank River.

The subsurface study area has approximately 400 drillhole penetrations through the McMurray Formation. The bulk of these holes were drilled in OSL 18 by Canadian Natural Resources or previous owners of the lease and stored at the Alberta Government Energy and Utilities Board Core Research Centre (EUB CRC). Due to the geologic complexity and importance of bitumen assays for possible production in this area, almost all of the 400 drillholes were cored. High recovery of core in the Athabasca Oil Sands area is relatively easy to obtain and inexpensive. The entire interval from surface casing to total depth is cored including the overlying Clearwater Formation, underlying Devonian sediments, and all non-reservoir intervals in the McMurray. This complete subsurface record and the shallow nature of the sediments allow the cores to be confidently correlated to surface outcrop exposures in nearby river valleys. The cores described for this study were chosen based on: 1) recovery (greater than 75% of the drilled depth); 2) formation intersection (all wells must penetrate Devonian and preferably the stratigraphic top of the McMurray Formation); and 3) drill date (more recent wells are better preserved).

Bechtel (1996) noted several of the inherent and valid shortcomings of describing core from the McMurray Formation. The first is the obscuring of sedimentary features including sedimentary and biogenic structures in the sand by bitumen saturation. This is a problem in core but not in weathered outcrop exposures where sun and rain have washed the bitumen from the sand. Due to the unconsolidated nature of the sands, core is taken in Poly-Vinyl Chloride (PVC) tubes and slabbed in half, leaving only a two-dimensional view of the core and increasing the likelihood of distortion and destruction of the core inside the tube during coring processes. Water sands from lows on the paleogeographic surface are rarely preserved due to the lack of bitumen that typically consolidates the sands of the McMurray Formation. These problems are inherent and cannot be avoided.

The 190 wells used for mapping in this study were chosen on the presence of a com-

plete log suite of gamma ray, resistivity, and density logs as well as a drill date not prior to 1972. Top picks on the well logs were made individually. Maps were made using the Golden Software program Surfer 8.

PREVIOUS WORK

The Athabasca Oil Sands deposit has long been recognized as a significant resource. The sheer scale and value attached to the oil sands has provided incentive to researchers in both the geological and engineering fields. In 1719 Wa-Pa-Su of the Cree Nation brought a sample of the oil sands to the Hudson's Bay Post located in Fort Churchill. He described the sands as "the pitch that flows out of the banks of the river". The indigenous peoples of northern Alberta had been using the sticky substance that dripped from the riverbanks as a canoe sealant for generations (Bell, 1885). Peter Pond became the first European to observe the oil sands in 1778. Sir Alexander Mackenzie, David Thompson, Sir John Franklin, and Sir John Richardson passed through the area between 1790 and 1880, making notes of this peculiar feature along the Athabasca River (Bell, 1885).

In the1880's, the Geological Survey of Canada conducted a reconnaissance survey of the area and published their findings (Bell, 1885). McConnell (1893) undertook a more detailed study of the oil sands for the Geological Survey of Canada, describing outcrop exposures near Fort McMurray. He also improperly correlated them with the Dakota sandstones in Minnesota.

The term McMurray was first proposed by F.H. McLearn in 1917 for strata containing "tar sands". McLearn felt that naming the oil sands Dakota was not appropriate due to the lack of fossil correlation material in the sediment. He also felt that "tar sands" was a lithological term and therefore inappropriate as a formation name (McLearn, 1917). Other studies in the early part of the twentieth century focused on physical and chemical properties inherent to the oil sands. These studies were concentrated on the overall size of this deposit and possible commercial development of this resource (Ells, 1914; 1926; Clark

and Blair, 1927). Sydney Ells, after whom the Ells River is named, and Karl Clark were instrumental in furthering the development of this resource during this time. Clark and S.M. Blair went as far as creating the first hot-water extraction pilot plant at the University of Alberta.

From the 1930's to 1950's, the research focus was shifted towards fine-tuning the local stratigraphy and establishing where the oil in the oil sands had come from. Russell (1932) and Warren (1933) detailed the local stratigraphy in the area with Badgely (1952) naming the basal member of the Clearwater Formation the Wabiskaw Member. Ball (1935), Sproule (1938; 1951), Link (1951), Hume (1949; 1951) and Corbett (1955) dealt with the complex debate as to where the oil had migrated from, and why the oil sands had bitumenized. Early petrological and mineralogical studies of the McMurray were completed by Mellon (1956), who also published some of the first biostratigraphic work in 1956 (Mellon and Wall, 1956).

From the late 1950's to the early 1970's, published work on the McMurray Formation was dominated by a single researcher (Carrigy, 1959; 1962; 1963a; 1963b; 1963c; 1966; 1967; 1971; 1973a; 1973b), who ushered in a popular depositional model and a new era of research on the geology of the Athabasca Oil Sands. His work was detailed; involving stratigraphy, mineralogy, sedimentology, paleontology, and paleocurrent analysis to generate a deltaic model that was not challenged until the late 1970's (Carrigy, 1966, 1967, 1971).

Studies through the 1970's and early 1980's focused on detailed local studies of the McMurray Formation rather than broad regional studies (Flach, 1977; James, 1977; Benthin and Orgnero, 1977; Nelson and Glaister, 1978; Mossop, 1980; Knight *et al.*, 1981; Wach, 1984; Fox, 1988). All of these studies but one (Flach, 1977) were focused within the subsurface, using petrophysical logs with limited core control.

Geological research on the oil sands was divided into two camps at this time based on the primary depositional model considered to be most correct. Both a fluvial model and

estuarine model were proposed in 1977 (Flach, 1977; MacCallum, 1977). Flach (1977) proposed a fluvial depositional model for the McMurray Formation that was continually published until 1985 (Mossop, 1978, 1980; Mossop and Flach, 1983; Flach 1984; Flach and Mossop, 1985). An estuarine depositional model was proposed by MacCallum (1977) with supporting researchers conducting independent studies (Stewart and MacCallum, 1978; Stewart, 1981; Pemberton *et al.*, 1982; Wach, 1984; Mattison *et al.*, 1989; Fox, 1988; Fox and Pemberton, 1989; Ranger and Pemberton, 1997; Wightman and Pemberton, 1997). Work by Smith (1985, 1987, 1988a, 1988b; 1989), using modern data for comparison, noted the tidal influence on McMurray sediments. Fox (Table 1, 1988) provides an overview of past interpretations developed from work on the McMurray Formation. Previous and current site-specific studies are shown in Figure 1.6. The inclusion of ichnological interpretations based on modern burrowing organism behaviors has supported the estuarine model for the McMurray Formation (Pemberton *et al.*, 1982; Ranger and Pemberton, 1992, 1997; Bechtel *et al.*, 1994; Yuill, 1995; Bechtel, 1996; Pemberton and Wightman, 1995; Wightman and Pemberton, 1997; Gingras *et al.*, 1998; Hein *et al.*, 2000; Harris *et al.*, 2001).

The current focus of study in the Athabasca Oil Sands is related to *in-situ* development and reservoir modeling. Gunter *et al.* (1997), Strobl *et al.* (1997), and Wightman *et al.* (1997) all deal with the complicated issue of tying depositional environment interpretations into possible production models. This work is built on detailed facies analysis and facies association comprehension in order to track the richest zones of the McMurray Formation in the shallow subsurface.

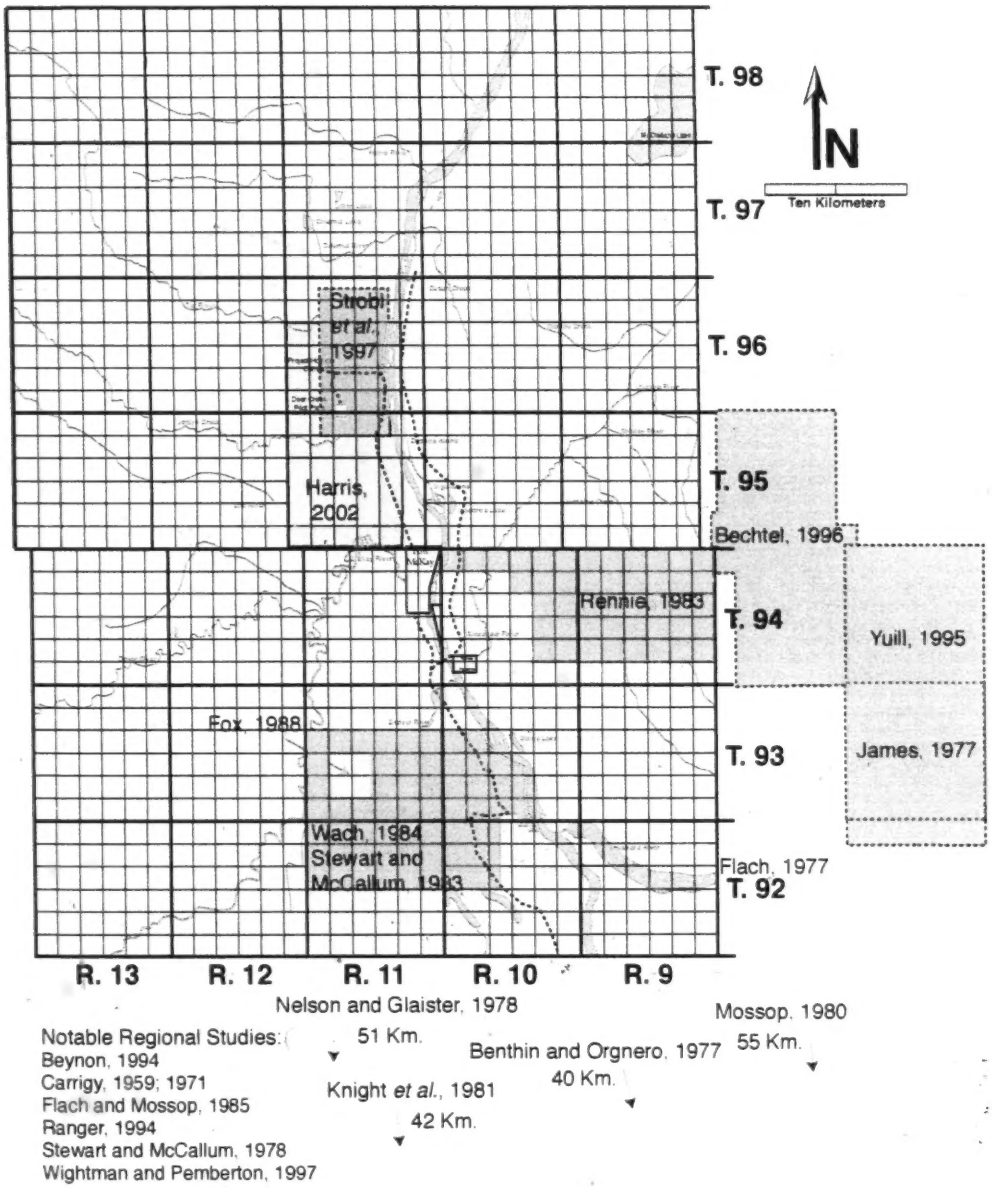


Fig. 1.6. The location of this and previous studies done on the sedimentology of the McMurray Formation in the north Athabasca region.

STRATIGRAPHY

PRE-CRETACEOUS SUCCESSION

The McMurray Formation unconformably overlies a succession of Devonian evaporites and carbonates (Stewart, 1963; Carrigy, 1973a; Wightman and Pemberton, 1997). The Devonian in turn unconformably overlies the Precambrian basement, depositionally thinning out on the Canadian Shield to the east and thickening westward (Norris, 1973). The Devonian strata dip to the west-southwest and subcrop successively younger towards the west (Martin and Jamin, 1963).

The Devonian sequence consists of: dolomite, anhydrite, gypsum, and halite of the Lower to Middle Devonian Elk Point Supergroup; limestone and dolomite of the Middle Devonian Slave Point Formation; and limestone and dolomite of the Upper Devonian Beaverhill Lake and Woodbend Groups (Carrigy, 1959; Norris, 1973). In the study area the Waterways Formation of the Beaverhill Lake Group is in direct, unconformable contact with the basal sediments of the overlying McMurray Formation.

The unconformity between Upper Devonian Beaverhill Lake Group carbonates and Cretaceous sediments is technically an angular unconformity that is widespread across most of northeastern and central Alberta (Glaister, 1959; Stewart, 1963; Park and Jones, 1985). This unconformity marks a significant break in deposition where the Devonian was exposed to subaerial erosion and weathering. There is no evidence of any deposition between Devonian and Early Cretaceous time in this area (Stewart, 1963). Mapping of this surface by inverting the isopach of the McMurray Formation, which is interpreted to infill lows on the unconformity, reveals a drainage system characterized by wide valleys and low rounded hills (Stewart, 1963; Smith, 1994; Ranger, 1994; Wightman and Pemberton, 1997).

CRETACEOUS SUCCESSION

The term Mannville Group applies to the Lower Cretaceous strata from the base of the pre-Cretaceous unconformity to the base of the Joli Fou Formation (Nauss, 1945). In the Athabasca Oil Sands area, the Mannville Group is made up of the McMurray, Clearwater, and Grand Rapids Formations (Williams, 1963). The lower part of the Mannville Group includes all strata below the Wabiskaw Member of the Clearwater Formation (Glaister, 1959). The McMurray Formation has been correlated to the lower part of the Mannville Group (Ellerslie or Basal Quartz)(Badgely, 1952) in central Alberta, the Dina Formation in the Lloydminster area and southern Saskatchewan (Glaister, 1959), the Gething Formation (Bullhead Group) in the Peace River Area, the Gladstone Formation (Blairmore Group) of the Alberta foothills (McLearn, 1945; Mellon, 1967), and the Sunburst Sandstone in southern Alberta (Williams, 1963) (Figure 1.7).

The Cretaceous succession in northeast Alberta includes: McMurray; Clearwater, Grand Rapids, Joli Fou, Pelican, and La Biche formations (Carrigy, 1959)(Figure 1.7). Only the McMurray and Clearwater Formations were identified in the study area.

The McMurray Formation (McLearn, 1917) is defined as the lowermost Cretaceous succession that unconformably overlies the Devonian carbonates and whose "top is placed at the base of a green sandstone". The McMurray Formation was divided by Carrigy (1959) into three informal members: lower, middle, and upper. These terms are still in use today, however the subdivision remains informal due to the complexity of regional correlations of the informal members. These simplified lithological subdivisions are not based on current sedimentological evidence and therefore hinder the depositional interpretation. They will not be used in this study with the exception of relating the interpretations given here to other studies. The lack of body fossils in the McMurray Formation has made it difficult to determine an exact age for the formation, however ages from Neocomian (Barremian) to Albian have been suggested for the McMurray Formation (Mellon and Wall, 1956; Vagvolgyi and Hills, 1969; Burden, 1984; Dolby, 1999). The consensus among current research-

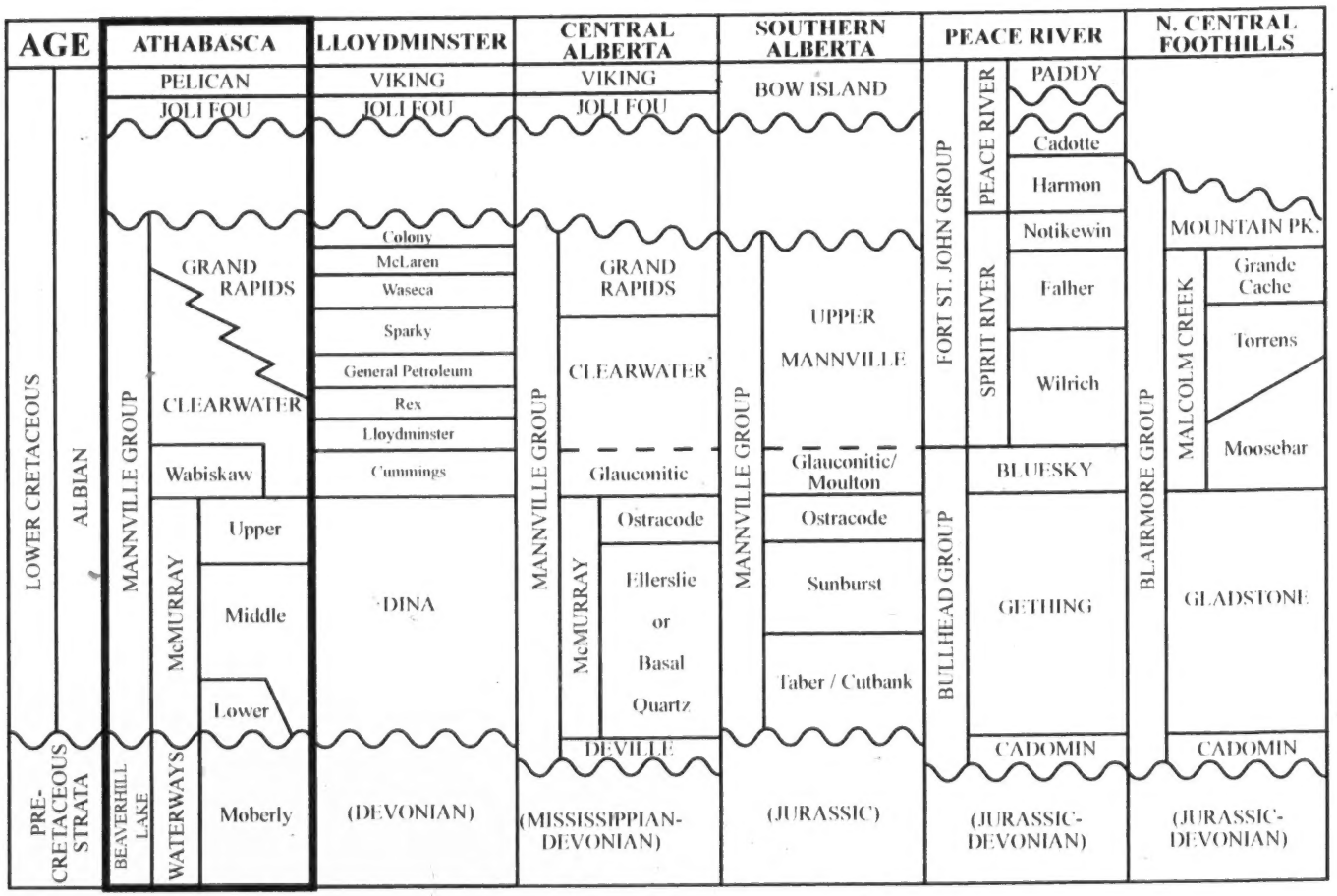


Fig. 1.7. Stratigraphic correlation chart of the Lower Cretaceous in Alberta. Parentheses indicate ages, not formations (modified from Yuill, 1995).

ers is that the McMurray is early Albian in age (Burden, 1984; Flach and Mossop, 1985; Ranger and Pemberton, 1992; Wightman and Pemberton, 1997; Dolby, 1999).

The Clearwater Formation (McConnell, 1893) conformably overlies the McMurray Formation in the study area. The base of the Clearwater Formation is defined as the base of glauconitic green sand comprising the Wabiskaw Member (Badgley, 1952). Neither the Wabiskaw Member nor the Clearwater Formation sediments found above the Wabiskaw Member were observed in the study area due to glacial erosion. The Clearwater Formation is of Lower Albian age (Burden, 1984; Flach and Mossop, 1985).

STRUCTURAL CONTROLS ON MCMURRAY FORMATION DEPOSITION

The extent and thickness of the McMurray Formation was dependant on the paleotopography and structure of the underlying Devonian strata at the time of deposition. The Precambrian basement and Devonian strata dip structurally towards the southwest at approximately 4.0m/km (Carrigy, 1959; Norris, 1973). Post-Cretaceous tilting was determined from correcting the Clearwater and Wabiskaw marker beds and is approximately 1.0m/km to the southwest (Martin and Jamin, 1963).

The McMurray Formation was deposited in a broad valley bound by the Canadian Shield to the east and the Wainwright Ridge-Grosmont High to the west (Stewart, 1963; Ranger and Pemberton, 1988; Wightman and Pemberton, 1997). The McMurray sediment subbasin, where the McMurray is arguably thickest (Carrigy, 1967; Ranger, 1994) formed as a result of subsurface dissolution of the underlying Prairie Formation (Elk Point Group) evaporites (Stewart, 1963). Dissolution of the evaporites caused the overlying carbonates of the Waterways Formation to collapse and subside, forming the basin where the sediments were accumulated (Carrigy, 1959; Stewart, 1963). Salt dissolution collapse continued during and after deposition of the McMurray Formation, accumulating 60.0m of collapse subsidence (Stewart, 1963). Dissolution of these evaporites is still occurring today

as evidenced by the numerous saline springs in the Athabasca Oil Sands, notably Saline Lake 38 kilometers southeast of the study area (Carrigy, 1959; Jardine, 1974).

Large paleovalleys formed by the salt dissolution collapse and less resistant carbonates developed on the unconformity surface (Stewart, 1963; Ranger, 1994). This created a localized central trunk drainage system, the "McMurray Channel Valley" (Ranger and Pemberton, 1992; Wightman and Pemberton, 1997) which played host to sediments that would eventually form the McMurray Formation (Stewart, 1963; Carrigy, 1967). Stewart (1963) was the first to note the trends of paleocurrent drainage and salt dissolution collapse. The spurs from main non-collapsed ridges may separate drainage valleys. Numerous north-northwest trending ridges parallel the subcrop edge (Martin and Jamin, 1963; Norris, 1973) including the Grosmont Ridge and Beaverhill Lake Ridge (Stewart, 1963). The Grosmont Ridge is a northern extension of the Wainwright and forms the western bounding edge of the McMurray subbasin. The Beaverhill Lake Ridge formed as a result of salt-dissolution collapse of underlying areas to the east of the ridge (Martin and Jamin, 1963; Stewart and MacCallum, 1978). Several smaller valleys follow a northeasterly trend and are inferred to be tributaries of the main northwesterly trending trunk drainage valley (Smith, 1994; Cant and Abrahamson, 1996)(Figure 1.8).

LOCAL STRUCTURE

The structure within the subsurface study area is a direct reflection of the unconformity surface below the McMurray Formation. The Ells River study area measures 8 kilometers by 16 kilometers and as such is a relatively small area compared to the entire Athabasca Oil Sands deposit (Figure 1.6). Structure in the area is fairly flat-lying with some minor highs and lows and a large dissolution collapse block in OSL 18 (Figure 1.9). Comparison of an isopach of the McMurray Formation (Figure 1.10) and structural map of the unconformity surface (Figure 1.9) reveal that the thickest sections of the McMurray Formation occur in these lows on the unconformity surface. The McMurray Formation in this area has a minimum thickness of 33.5 meters in well AA/05-04-095-11W4/0 and in the

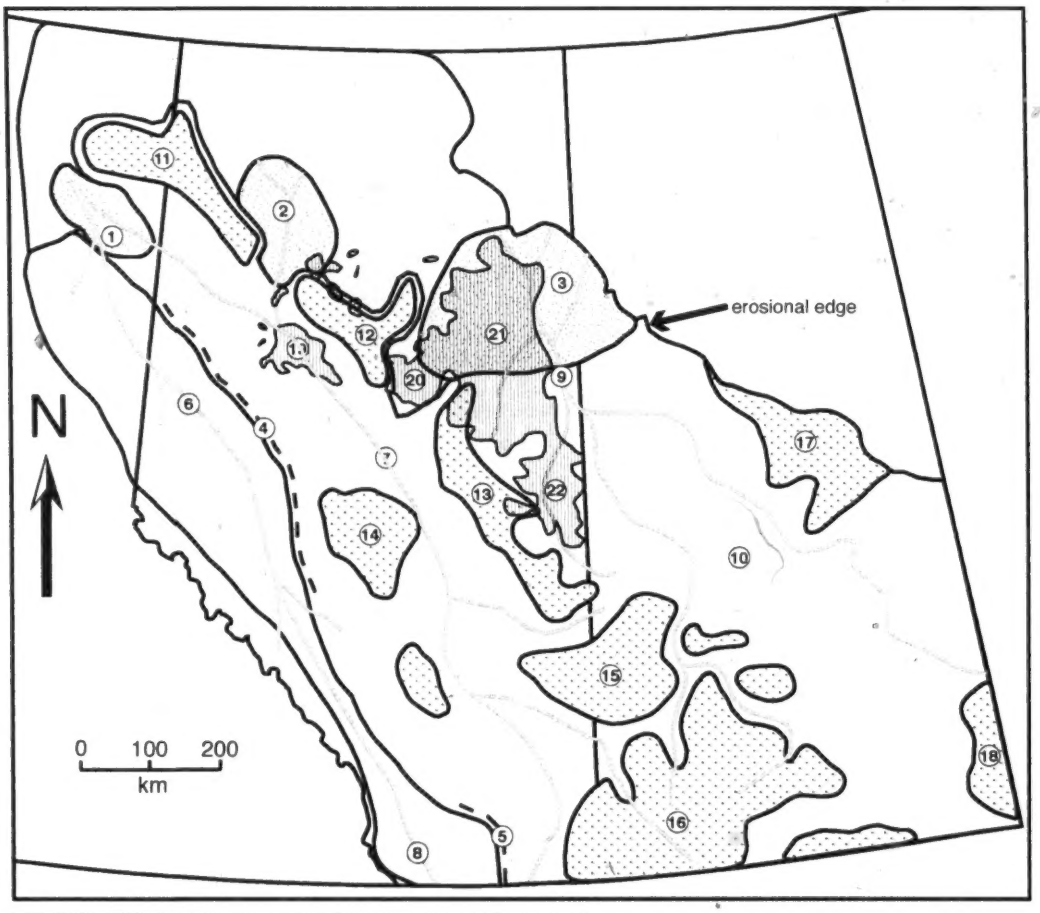
southwest corner of the study area and a maximum thickness of 103 meters in the northeast corner of the study area in well AA/15-10-096-11W4/0. The northeast corner is also where the highest amount of salt-dissolution collapse has occurred. In many locales in the study area, the original McMurray Formation depositional thickness cannot be established due to glacial erosion of the upper McMurray sediments. The Ells River erosional valley is almost 2 kilometers wide in areas and has eroded much of the upper sediments. The overall succession of McMurray sediments tips towards the northwest due to post-depositional salt-dissolution collapse north of the study area (Ranger, 1994).

The thick McMurray deposits to the northeast are related to the salt-dissolution collapse zone noted on figure 1.9. This zone has seen continual collapse beginning sometime before the Cretaceous and subsiding up to the present day as shown by the Wabiskaw topography (Figure 1.11) and the current location of the Athabasca River (Figure 1.6).

GEOLOGICAL FRAMEWORK

The sediments of the Western Canada Sedimentary Basin were deposited in a passive margin to foreland basin setting. The collision and subsequent accretion of terranes to the North American craton during Middle Jurassic time resulted in the development of the Western Canada Foreland Basin (WCFB) (Leckie and Smith, 1992; Stott, 1993). Foreland basins are typically asymmetric, with a deeper axis closest to the fold-thrust belt as a result of subsidence due to thrust-belt loading and sediment loading in the basin (Leckie and Smith, 1992). The sediments in the Western Canada Foreland Basin thicken westward as a result. The basin was filled with sediments derived from erosion of the Cordillera to the west, the Canadian Shield to the east, and previously deposited local material (Cant, 1989; Beaumont *et al.*, 1993).

The clastic wedge of the WCFB is subdivided into sedimentary cycles based on the identification of significant unconformities (Leckie and Smith, 1992; Stott, 1993). Both Stott (1984, 1993) and Leckie and Smith (1992) classified wedges in the Rocky Mountain



LEGEND:

1. Sikanni Chief Delta
2. Keg River Delta
3. McMurray Estuary
4. Fox Creek Escarpment
5. Taber Escarpment
6. Spirit River Channel Valley
7. Edmonton Channel Valley
8. Cutbank Channel Valley
9. McMurray Channel Valley
10. Assiniboia Channel Valley
11. Keg River Highlands
12. Red Earth Highlands
13. Wainwright Highlands
14. Pembina Highlands
15. Kindersley Highlands
16. Medicine Hat - Swift Current Highlands
17. Molanosa Highlands
18. Moosomin Highlands
19. Peace River Oil Sands
20. Wabasca Oil Sands
21. Athabasca Oil Sands
22. Cold Lake Oil Sands

area of non-deposition
nearshore deposits
fluvial deposits
shallow shelf deposits
alluvial deposits

Fig. 1.8. Paleogeography of the Western Canada Sedimentary Basin during Early Cretaceous McMurray (and equivalents) time (modified from Smith, 1994; Hubbard, 1999).

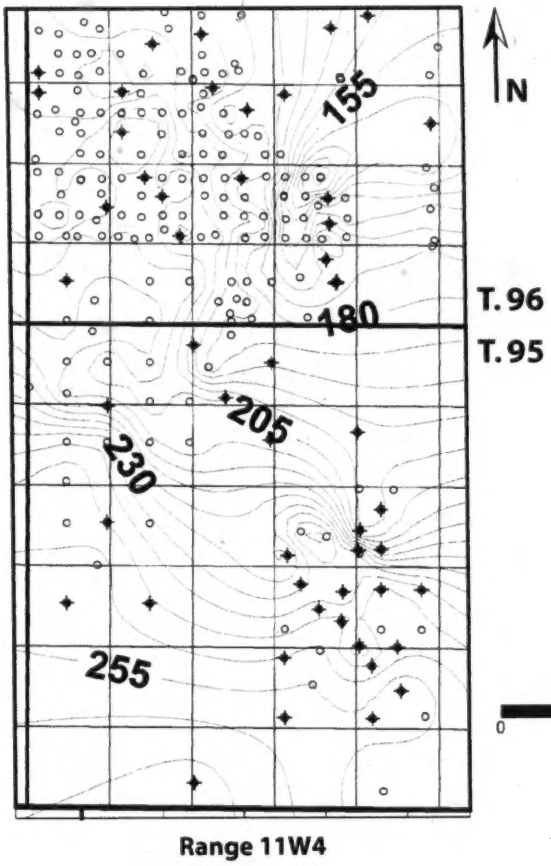
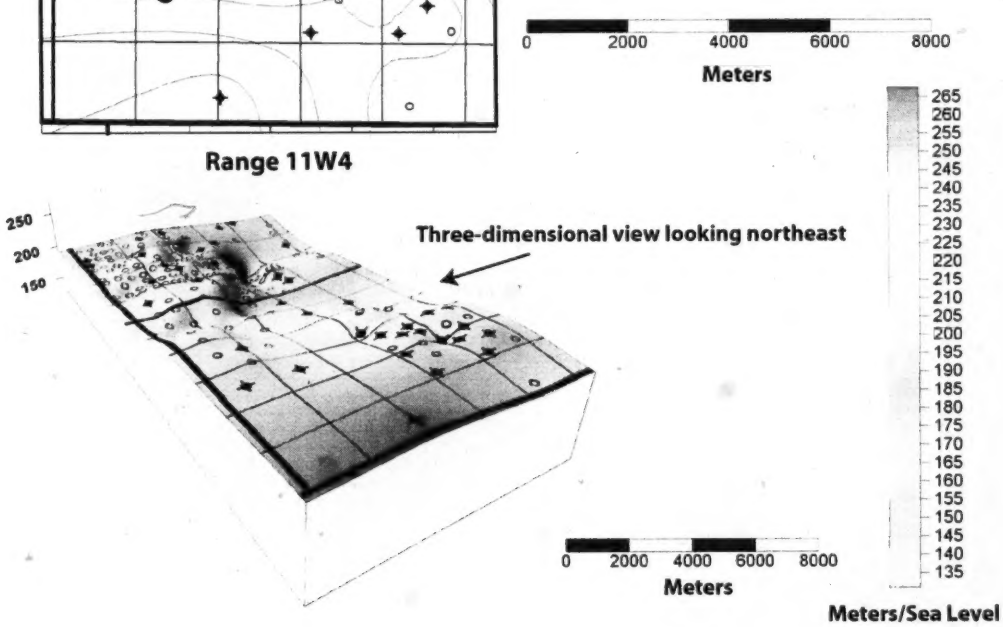


Fig. 1.9. The local structure on the present day unconformity surface. Weathering and salt-dissolution collapse has altered the pre-Cretaceous unconformity since the deposition of the McMurray Formation (Fig. 1.4). Below is a three-dimensional rendering of this surface color coded for depth. All measurements in meters/sea level.



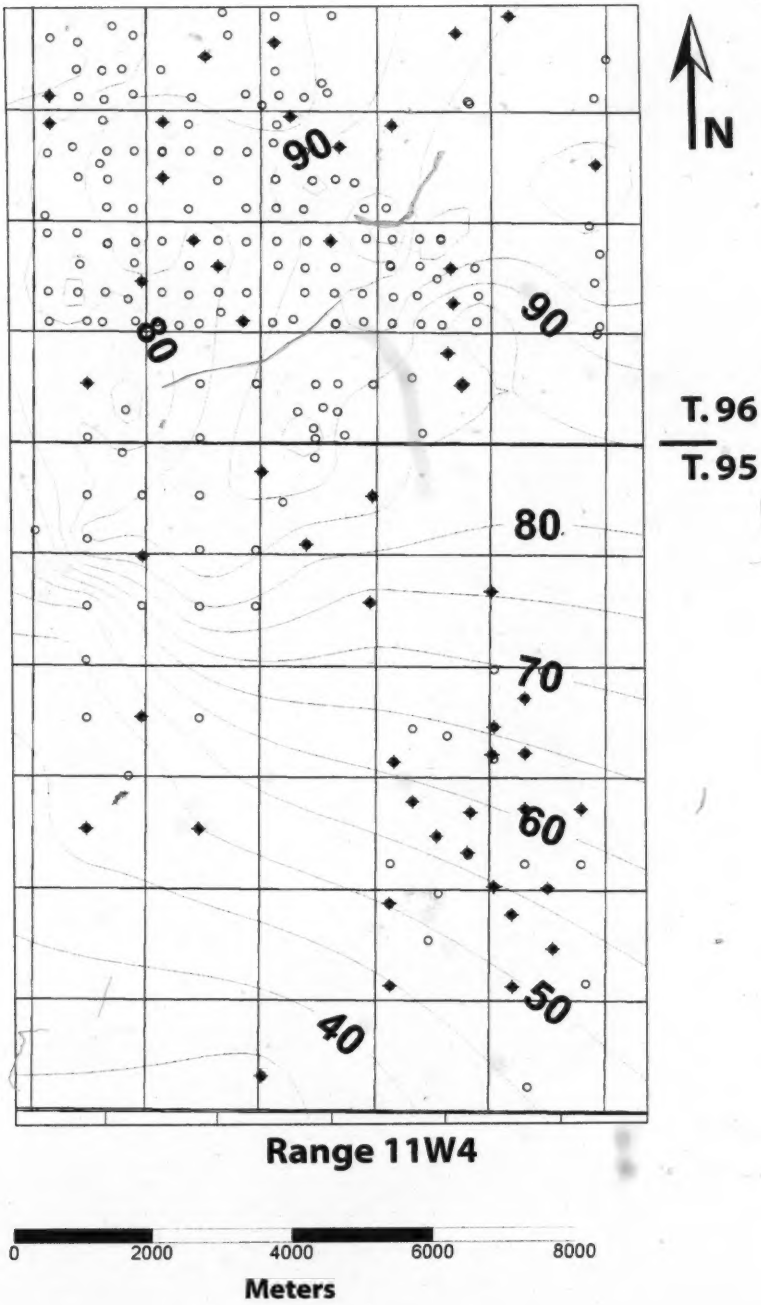


Fig. 1.10. An isopach of the McMurray Formation in the Ells River Study Area. Contours are drawn at 10 meter intervals.

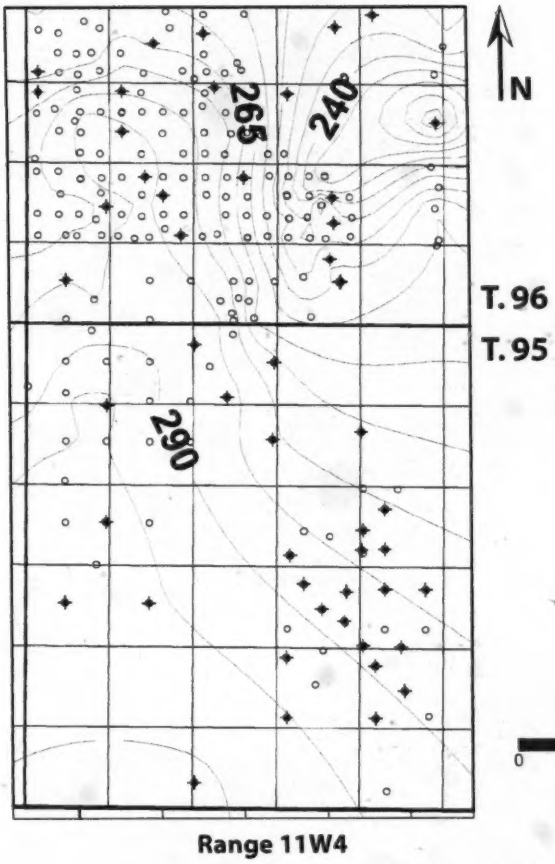
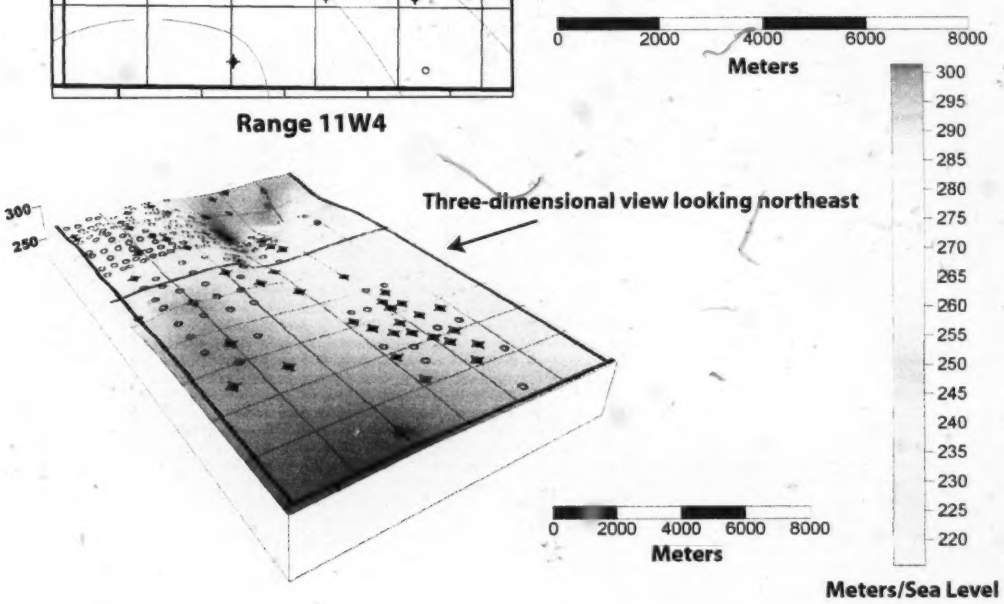


Fig. 1.11. The present day topography of the Wabiskaw flooding surface displaying post-depositional changes in local structure. Below is a three-dimensional rendering of this surface color coded for depth. All measurements are in meters/sea level.



Foothills to the Jurassic Columbian Orogeny. While Stott (1993) identified 3 wedge divisions, Leckie and Smith (1992) devised a systematic division of 5 cycles within the foreland basin. The first coeval clastic wedge/cycle consists of Jurassic and early Cretaceous sediments of the Fernie Formation, the Minnes and Kootenay Groups, and the Nikanassin Formation (Leckie and Smith, 1992; Stott, 1993). These sediments are only preserved in the western reaches of the WCFB insinuating that sedimentation may have only occurred in the foothills (Cant, 1989; Cant and Abrahamson, 1996). It is more likely that sediments deposited further to the east were eroded due to the compressional uplift (Hanson, 2001). The second jointly identified wedge unconformably overlies the first wedge/cycle and includes the Lower Cretaceous sediments of the Blairmore Group of the foothills, Luscar, and Fort St. John Groups of northwestern Alberta and British Columbia, and the Mannville Group of central and northeastern Alberta (Leckie and Smith, 1992; Stott, 1993). The subsequent sequences reflect depositional conditions before the Laramide orogeny (Late Cretaceous to Paleocene) (Leckie and Smith, 1992; Stott, 1993).

The Blairmore and Mannville Groups were deposited on an unconformity that was deeply incised by three main northwest trending drainage valley systems separated by topographic ridges (Figure 1.8): the Spirit River Valley system, the Edmonton Channel Valley, and the McMurray Valley system (Ranger, 1994; Wightman and Pemberton, 1997) that was formerly known as the St. Paul Channel of Williams (1963), or the Assiniboia Valley of Leckie and Smith (1992). The Spirit River Valley system trends northwest along the western edge of the basin and drained most of western Alberta and the western United States (Ranger, 1994; Leckie and Smith, 1992). The Edmonton Channel Valley trends north-northwest and is inferred to have drained southeastern Alberta and Saskatchewan (Williams, 1963; Ranger, 1994). The Edmonton Channel may have drained into the Boreal Sea to the north or it may have been a late-joining tributary of the Spirit River Valley system (Ranger, 1994). The Wainwright Ridge (Grosmont High) to the east of the Edmonton Channel Valley most likely served as an axial ridge to separate the Edmonton Channel

Valley system with the McMurray Valley system. The McMurray Valley system developed due to subsidence caused by formation-water migration dissolution of the Middle Devonian Prairie Formation evaporites along the eastern edge of the Alberta Basin (Stewart, 1963; Ranger, 1994). The basin configuration for sediments of the McMurray Formation was a northwesterly trending trough bounded on the east by the Canadian Shield and on the west by the Grosmont High/Wainwright Ridge.

Southward stepping marine incursions of the Boreal Sea flooded the major valley systems, drowning river systems and influencing the development of nearshore marine depositional systems (Williams, 1963; McLean and Wall, 1981; Wightman and Pemberton, 1997). Each of the three valley systems reacted differently to the marine incursion depending on sediment supply and topography (Ranger, 1994). The transgression occurred due to: subsidence of the Alberta Basin from crustal loading during the Columbian Orogeny, subsidence of the McMurray Basin due to salt dissolution collapse, and the global eustatic sea-level rise that was occurring during the Lower Cretaceous (Caldwell, 1984; Fox, 1988; Leckie and Smith, 1992; Cant and Abrahamson, 1996). The Boreal Sea continued transgression southward during the Early Albian, depositing the deep-water shales of the Clearwater Formation (Williams, 1963). At the end of Mannville deposition, the Boreal Sea had joined with the Gulfian Sea transgressing from the south, forming a shallow epicontinental sea, the Western Interior Seaway, into which Upper Cretaceous marine sediments were deposited (James, 1977; Leckie and Smith, 1992).

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CHAPTER 2 - THE EXTENT OF TIDAL AND BRACKISH INFLUENCE ON THE SEDIMENTS OF THE MCMURRAY FORMATION, NORTHEAST ALBERTA, AND THE EVOLUTION OF A GENETIC STRATIGRAPHIC MODEL: EVIDENCE FROM DETAILED FACIES ANALYSIS

INTRODUCTION

The Lower Cretaceous McMurray Formation contains approximately 902 billion barrels (143 billion cubic meters) of bitumen (AEUB, 2000). The Athabasca Oil Sands deposit, which is hosted by the McMurray Formation, is the world's largest accumulation of hydrocarbons (Meyer and Duford, 1989) and the largest of the four oil sands deposits in Alberta. The other three deposits are the Peace River, Cold Lake, and Wabiskaw accumulations (Fig. 2.1).

The Athabasca Oil Sands deposit can be divided into surface-mineable and in-situ recovery areas based on the depth of the oil sand (~90m). Currently, production from mining in the Athabasca Oil Sands contributes over 16% of Canada's oil production. The ratio of reserves to production in the surface mineable area suggests significant increases in production are possible (Singh *et al.*, 1991). In-situ developments are rapidly coming on-stream in the Athabasca Oil Sands as the major portion of the resource cannot be recovered using surface mining techniques (Fig. 2.1). Steam Assisted Gravity Drainage (SAGD) is rapidly becoming a popular method of production although detailed knowledge of the reservoir stratigraphy is paramount to a successful operation.

The objective of this research is threefold: 1) to describe and quantify the sediments exposed along the Ells River located in Townships 95 and 96 in Range 11W4 and local outcrops exposed along the Athabasca River, northeastern Alberta; 2) compare the data

Fig. 2.1. The location of the major oil sand deposits of Alberta. The darker green area indicates the surface mineable area of the Athabasca Oil Sands.

from the outcrops to nearby core data; and 3) complete a genetic stratigraphic model for the McMurray Formation in this area through facies analysis and facies association identification. Previous researchers in the McMurray Formation described the stratigraphy as being some of the most complex in the Western Canada Sedimentary Basin (Carrigy, 1971; Mossop, 1980; Ranger and Pemberton, 1992, 1997; Wightman and Pemberton, 1997). Regional work by Flach (1984) and Ranger and Pemberton (1988, 1992, 1997) have identified distinct stratigraphic horizons interpreted as fluvial, estuarine, and shoreface environments using large and complete databases of petrophysical logs and core descriptions. Small study areas are typically hampered by limited databases but allow for very detailed sedimentologic interpretations of the available data.

The study area for this research is focused around the partially described Ells River outcrops in the northwest quadrant of the surface mineable area (Fig 2.2, Fig. 2.3). The outcrops along the Ells River in Township 95 and 96 in Range 11W4 were first identified by Ells (1926) and were most recently geologically described in the literature by Strobl *et al.* (1997), who completed a sedimentologic and stratigraphic study of cores and outcrops to the north of and inside this study area, and Hein *et al.*, (2001), who compiled a regional database of outcrop exposures. Strobl *et al.* (1997) and Hein *et al.* (2001) were limited by access to only the first four or five outcrops up the Ells River from the outlet to the Athabasca River. Hein *et al.* (2001) were able to describe the outcrops located near the Ells River pumping station by road access. These outcrops are the last exposures of McMurray Formation to the west along the Ells River. This study utilized helicopters to access the outcrops between the Ells River mouth sections and the pumping station sections. It is at these outcrops where more complete sections of the McMurray Fm. are exposed (Fig. 2.3). Although outcroppings of McMurray Formation along the banks of the Ells River are very common, only outcrops comprising uncovered exposures thicker than twenty meters were identified numerically and used in this study. Outcrops 11-16 are the focus of this study. Core data comprises wells drilled no earlier than 1972 and were selected based on the quality of the core (preservation), proximity to outcrops, and the thickness of McMurray sediment cored. The cores examined in detail are highlighted in figure 2.2.

PREVIOUS WORK

The Athabasca Oil Sand has long been recognized as a significant resource. The sheer scale and economic value attached to the surface-mineable oil sands deposit has provided incentive to researchers in both the geological and engineering fields. The term McMurray was first proposed by F.H. McLearn (1917) for strata in the Athabasca region containing tar sands. The work of M.A. Carrigy (1959, 1962, 1963a, 1963b, 1963c, 1966,

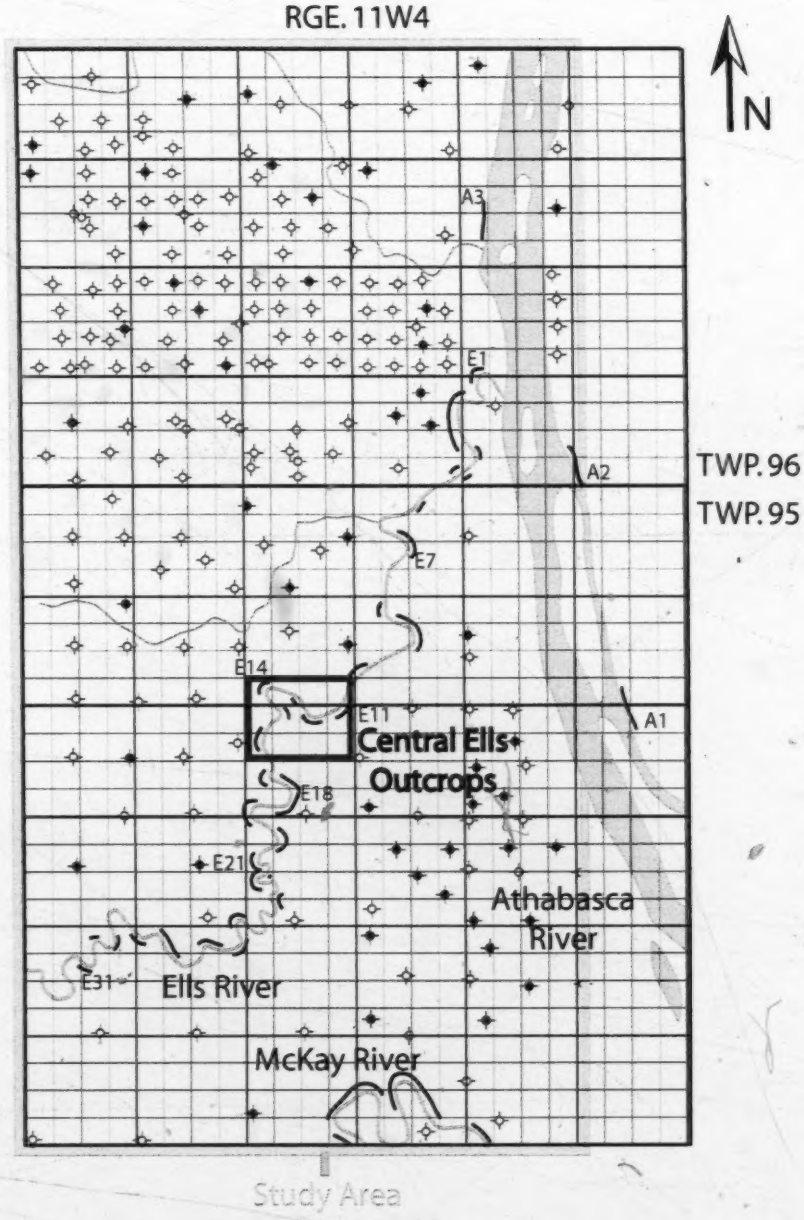


Fig. 2.2. Location of the outcrops and core examined for this study. The outcrops along the Ells River are named after initial identifications made by Sydney Ells (1926). The outcrops are numbered upstream from the outlet on the Athabasca. Cores described for this study are represented by filled icons.

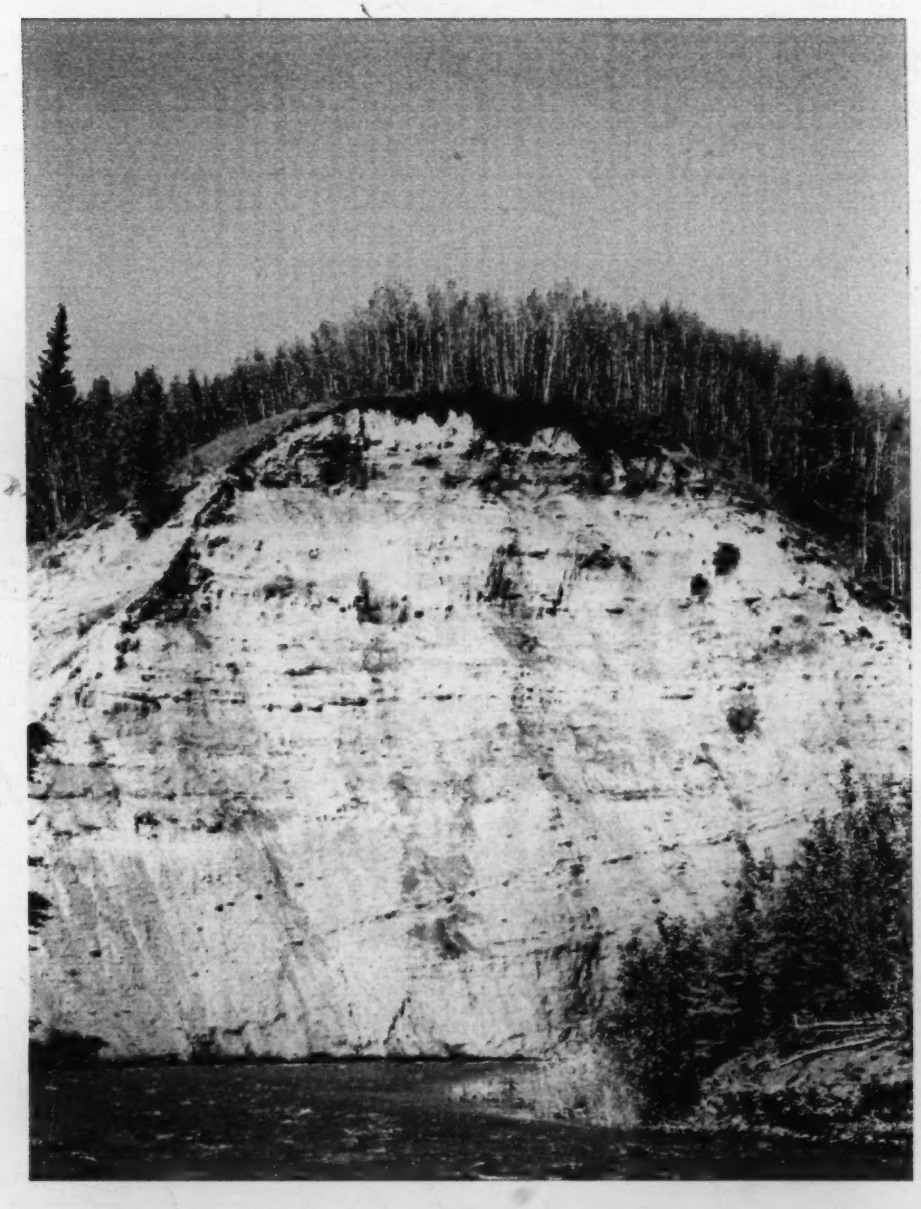


Fig. 2.3. Outcrop E14 along the Ells River. The exposed section is over 75 meters of continuous McMurray Formation. Although the underlying unconformity is not present at this outcrop, it is present east along the banks of the Athabasca River. The overlying Wabiskaw Member of the Clearwater Formation is not present at this outcrop.

1967, 1971, 1973a, 1973b) involved detailed stratigraphy, mineralogy, sedimentology, paleontology, and paleocurrent analysis to generate a deltaic model that was unchallenged until the late 1970's. Due to subsequent work by many scientists, alternate depositional models became available to researchers studying ancient deposits, and Carrigy's deltaic model was challenged.

Several studies of the McMurray Fm. were focused on small geographic areas rather than broad regional studies (James, 1977; Benthin and Orgnero, 1977; Nelson and Glaister, 1978; Mossop, 1980; Knight *et al.*, 1981; Wach, 1984; Fox, 1988; Yuill, 1995; Bechtel, 1996; Strobl *et al.*, 1997). Only the work of Flach (1977) attempted to define a paleoenvironmental interpretation of the McMurray Formation based on outcrop exposures..

A fluvial model and an estuarine model for the McMurray Fm. were proposed in 1977 (Flach, 1977; MacCallum, 1977). The estuarine depositional model proposed by MacCallum (1977) has been corroborated with researchers conducting independent studies (Stewart and MacCallum, 1978; Stewart, 1981; Pemberton *et al.*, 1982; Wach, 1984; Mattison *et al.*, 1989; Fox, 1988; Fox and Pemberton, 1989; Bechtel *et al.*, 1994; Wightman and Pemberton, 1997; Hein *et al.*, 2000).

The incorporation of ichnological interpretations has supported the estuarine model for the McMurray Formation (Pemberton *et al.*, 1982; Ranger and Pemberton, 1992, 1997; Bechtel *et al.*, 1994; Yuill, 1995; Bechtel, 1996; Pemberton and Wightman, 1995; Wightman and Pemberton, 1997; Gingras *et al.*, 1998). The estuarine depositional model of the McMurray Formation is now currently accepted by almost all researchers, including this present writer.

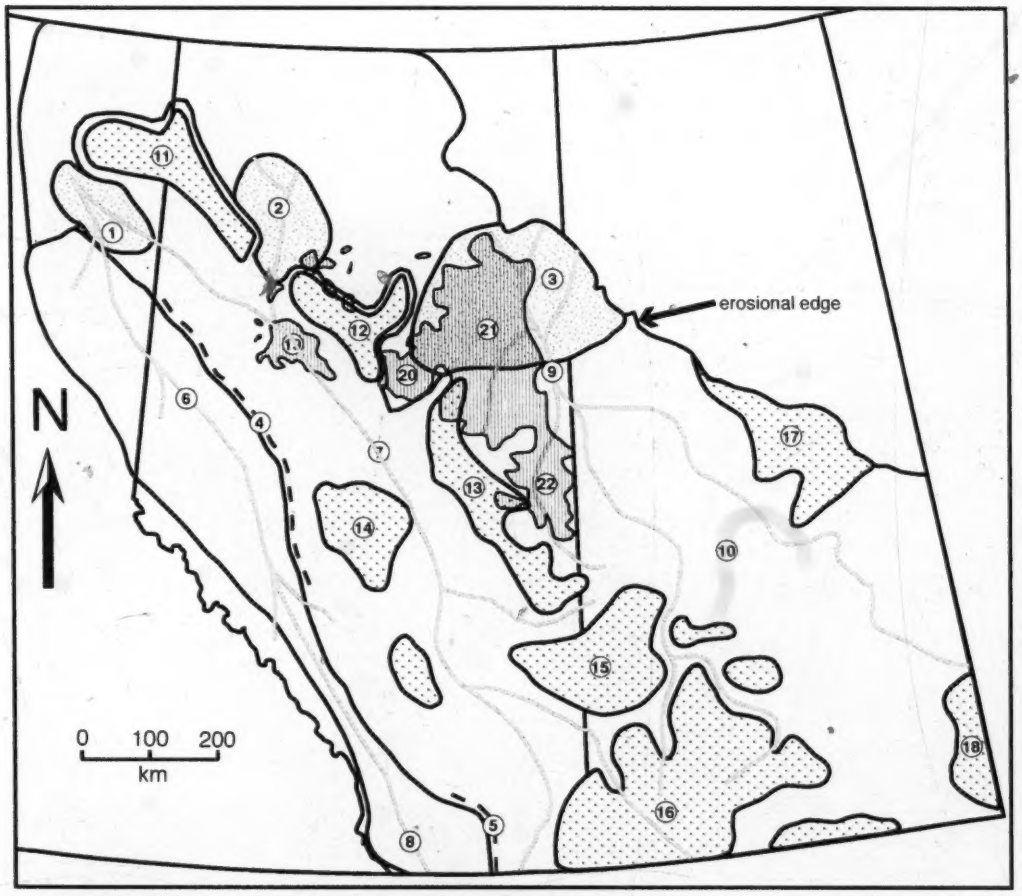
TECTONIC SETTING

The sediments of the McMurray Formation were deposited on the sub-Cretaceous

unconformity in northeast Alberta, which exposed middle to upper Devonian carbonate rocks (Ranger, 1994; Bechtel, 1996; Wightman and Pemberton, 1997). The unconformity in this area developed as a result of the Cordilleran orogeny that transformed the basin from a passive margin setting to a foreland basin (Stott, 1993). The orogeny caused uplift and erosion to the east near the exposures of the Canadian Shield (Leckie and Smith, 1992). Dissolution of the Devonian Prairie Evaporites Formation through eastward basinal water flow caused structural collapse in northeast Alberta as a series of faults and grabens (Ranger, 1994; Wightman and Pemberton, 1997). The paleo-lows created by the dissolution of the evaporites were exploited by fluvial drainage systems in northeast Alberta, carrying eroded Canadian Shield material towards the Boreal Sea to the north (Carrigy, 1971). These valleys subsequently became host to sediments of the McMurray Formation during the transgression of the Boreal Sea southward which drowned the river valleys and created an estuarine environment (Fig. 2.4)(Wightman and Pemberton, 1997).

The transgression of the Boreal Sea occurred due to: subsidence of the Western Canada Sedimentary Basin from crustal loading during the Columbian orogeny, subsidence of the local basin in the Athabasca region due to salt dissolution collapse, and the global eustatic sea-level rise that was occurring during the Early Cretaceous (Caldwell, 1984; Fox, 1988; Leckie and Smith, 1992; Ranger, 1994). The Boreal Sea continued transgression southward during the Early Albian, briefly regressing during the middle Albian before transgressing as the Comanche Sea. It subsequently joined with the Gulfian Sea transgressing from the south to form a shallow epicontinental sea known as the Western Interior Seaway (James, 1977; Caldwell, 1984).

The McMurray Formation comprises the basal sediments of the Mannville Group in the Athabasca region (Fig. 2.5). These sediments are equivalent to the Cadomin and Gething Formation sediments of the Bullhead Group and Luscar Group to the west, and Dina sediments to the east. The McMurray depositional system was separated from the western part of the basin by the Wainwright Ridge/Grosmont High to the west (Fig.



LEGEND:

1. Sikanni Chief Delta
2. Keg River Delta
3. McMurray Estuary
4. Fox Creek Escarpment
5. Taber Escarpment
6. Spirit River Channel Valley
7. Edmonton Channel Valley
8. Cutbank Channel Valley
9. McMurray Channel Valley
10. Assiniboia Channel Valley
11. Keg River Highlands
12. Red Earth Highlands
13. Wainwright Highlands
14. Pembina Highlands
15. Kindersley Highlands
16. Medicine Hat - Swift Current Highlands
17. Molanosa Highlands
18. Moosomin Highlands
19. Peace River Oil Sands
20. Wabasca Oil Sands
21. Athabasca Oil Sands
22. Cold Lake Oil Sands

area of non-deposition
nearshore deposits
fluvial deposits
shallow shelf deposits
alluvial deposits

Fig. 2.4. Early Cretaceous paleogeography map of the Western Canada Sedimentary Basin. The study area is located in the surface mineable portion of the Athabasca Oil Sands deposit (modified from Smith, 1994).

2.4)(Carrigy, 1971; Flach, 1984).

METHODS

Outcrops along the Ells and Athabasca Rivers are typically unconsolidated and relatively steep (Fig. 2.3). This required the author to use climbing ropes and equipment to safely access the exposures. Detailed strip logs were generated at several horizontal intervals down the outcrop faces. These strip logs included lithologic description, sedimentological and ichnological data, and surface continuity information. The outcrops were logged by hand and the information was then transferred to a computer aided logging program (AppleCORE©). Gamma-ray curves were generated along the outcrop face using a portable scintillometer in an effort to compare these curves with log signatures in the core database. Core was transcribed directly into the AppleCORE© program.

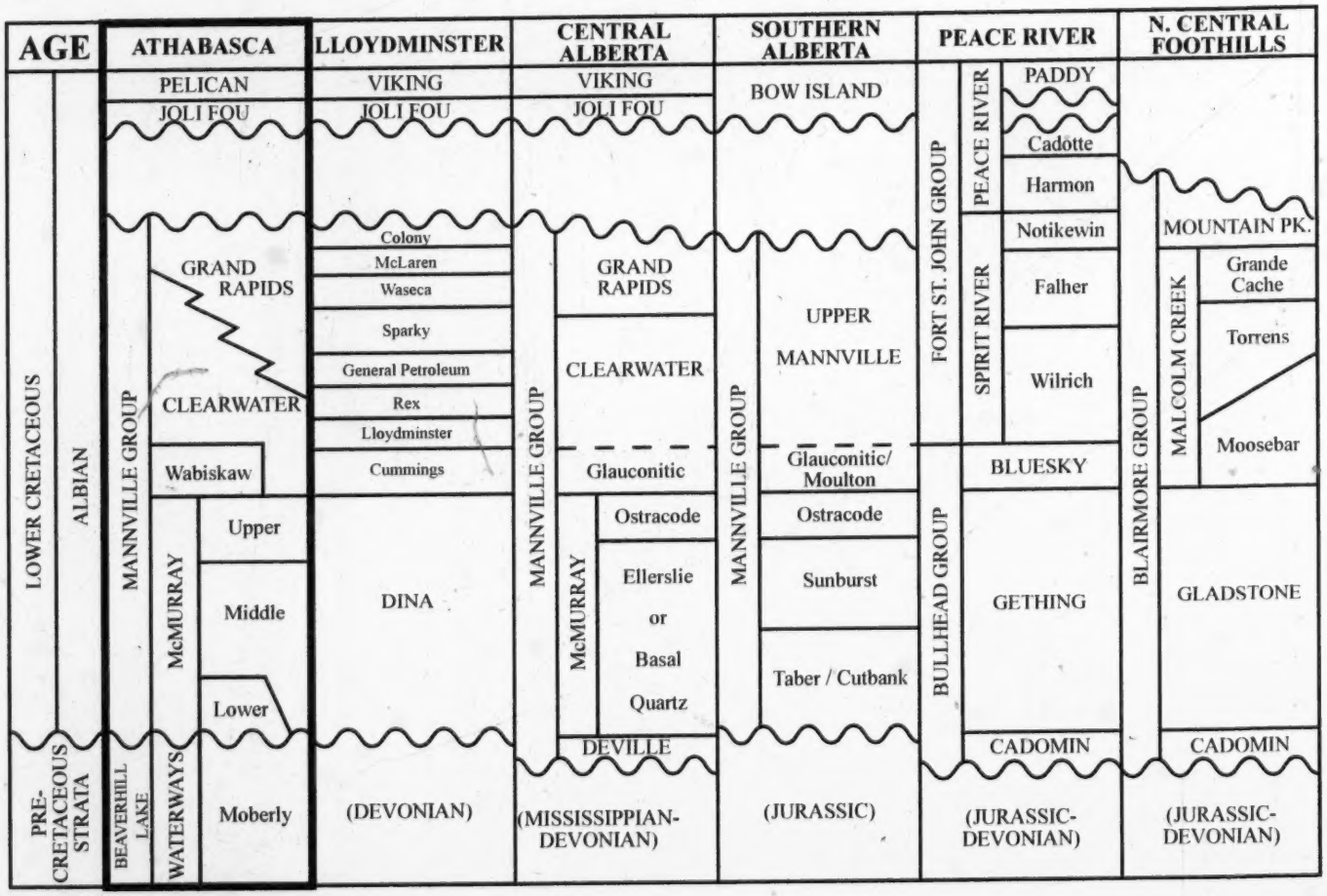


Fig. 2.5. Stratigraphic correlation chart of the Lower Cretaceous in Alberta. Parentheses indicate ages, not formations (modified from Yuill, 1995).

FACIES DESCRIPTION AND INTERPRETATION

The sediments of the McMurray Formation near Ells River can be grouped into distinguishable facies. Facies are a combination of sedimentologic and ichnologic criteria that allow genetically linked fabrics to be separated from unrelated fabrics. For example, burrowed inclined bedded sand is considered a separate facies from burrowed horizontally bedded sand. Certain sedimentologic criteria may be common to several facies: breccia in inclined sand is a single facies when it occurs uninterrupted over a sufficient interval, but it can also be a component of several other facies. Contacts, sedimentary structures, lithologic accessories, and ichnology are used as descriptive features of each facies. These characteristics are analyzed to ascertain a number of different depositional environments for each facies. Genetic stratigraphic interpretations are not included in the facies description and interpretation, as they will be built from the various associations of the facies.

Four major facies are delineated by a basic set of descriptive parameters. These four facies are then subdivided into 18 subfacies categorized by more detailed characteristics. The four major facies are: horizontally bedded sands (F1), inclined heterolithic sediments (F2), horizontally interbedded sand and mud (F3), and horizontally bedded silts and muds (F4). Table 2.1 compares each of the facies based on contacts, sedimentary structures, lithologic accessories, ichnology, and interpretation. Facies associations and the accompanying association interpretations will be presented after the individual subfacies (facies) are described and interpreted.

FACIES 1 (F1) HORIZONTALLY BEDDED SAND

Several subfacies found in sediments of the McMurray Fm. consist of a sand-dominated grain size and display horizontal bedding. The facies of type one comprise four sub-facies: granular grading sand (F1a), high-angle cross-stratified sand (F1b), small-scale

Description	Occurrence / Contacts	Physical Structures	Texture and Lithologic Accessories	Ichnologic Characteristics	Interpretation
Facies 1 (F1) horizontally bedded sand F1a granular grading sand	• generally low in the succession • generally sharp lower contact • grades upwards into sandy facies • can overly Devonian unconformity surface	• low- to high-angle cross-stratification • lags present	• minor sand beds • pebbles • breccias • carbonaceous debris • coal fragments • siderite and pyrite present • concretions present • repeated graded bedding • poorly to well sorted • subangular to angular grains	• absent of bioturbation	• high energy environment • deposited in shallow water in an overall unidirectional current • deposition as basal fluvial sediment
F1b high-angle cross-bedded sand	• sharp basal contact • abrupt to sharp upper contact • commonly overlain by F2 • typically 40 to 250 cm in thickness	• current ripples • climbing ripples • grain striping • thinly laminated beds • high-angle cross bedded • tabular to trough cross-stratified • back-flow/counter-current ripples	• very rare mud laminae • silt laminae • well sorted • subangular to subrounded grains • fine sand grain size	• rare to low trace fossil abundance • low diversity Rare Co. Sk, Cy • common escape structures	• moderate to high energy environment • sediment transport primarily in one direction • more marine nature than F1a (Co) • 3-4 meters of water depth • back-flow ripples indicate minor transport in opposite direction • shifting substrate • deposition as subtidal bars
F1c small-scale cross-stratified sand	• sharp basal contact • abrupt upper contact • commonly overlain by F1b, F2b, F2e, F3a • typically 25cm to 1 meter in thickness	• current ripples • rare climbing ripples • planar-tabular to trough cross-stratification • can form wavy to lenticular bedding • combined flow ripples	• mud laminae • silt laminae • organic detritus • well sorted grain size • subangular to subrounded grains • fine sand grain size	• rare to low trace fossil abundance • low diversity Rare Sk, Cy • common escape structures	• moderate to high energy environment • sediment transport primarily in one direction • shallow water depth • deposition on the surface of subtidal bars or on flood-inundated tidal flats
F1d laminated to well-burrowed sand	• sharp to gradational base • sharp to gradational top • consistent bioturbate texture • typically overlies F2 and F3 • commonly intercalated with F3d, and F3e • can underly Wabiskaw Member	• oscillation ripples • wavy parallel and low angle parallel laminated (distal HCS) • cm scale bedding w/ fining upwards lamination sets • thinly laminated beds intercalated with bioturbated beds of 1-30 cm	• mud laminae • silt laminae • organic detritus • fine sand grain size • well sorted grain size • subrounded to rounded grains	• moderate to high trace fossil abundance • high diversity Sk, Th, Te, Pl, Pa, Di, Ro • average to large size • distal Skolithos ichnofacies	• high energy environment • deposition below fair weather wave base under bidirectional current • evidence of wave reworking • shallow water depth • mesohaline to marine salinities as shown by the ichnological signature • deposition in an open bay/ protected shoreface

Table 2.1. Facies Chart comparing facies identified in this study.

Description	Occurrence / Contacts	Physical Structures	and Lithologic Accessories	Ichnologic Characteristics	Interpretation
Facies 2 (F2) inclined heterolithic sediments					
F2a mud-clast breccia in inclined sand	• lower contact sharp, or grades over 20cm • may grade across 10-20 cm when over-lying F1a • commonly sits on F1a, F1b, F2b-d • can overly Devonian unconformity surface	*Matrix* • planar tabular to inclined beds • breccia clast size 0.5mm to 10cm dia. • rare current ripples	• rip-up clasts • rare organic detritus • consistent grain size • very well sorted • subangular to subrounded grains	• absent of bioturbation	• low to moderate energy environment • deposition in unidirectional currents • fluvially influenced bank-collapse-breccias • element of channel margin rip-ups • rapid emplacement
		Clasts • thinly laminated bedding • massive bedding	• rare organic detritus	• absent of bioturbation	
F2b sand-dominated inclined heterolithic stratification	• sharp to gradational base • gradational top • can up to 20 meters thick • commonly overlies F1a, F1b, F2 • can overly Devonian unconformity surface	• rare current ripples • rare climbing ripples • reactivation surfaces • double mud drapes • lenticular to wavy bedding • inclined to slightly inclined bedding • thinly laminated beds	• silt laminae • mud laminae • carbonaceous debris • rare wood fragments • rare rip-up clasts • grain size is fine sand • well sorted • subangular to subrounded grains	• generally absent of bioturbation • rare Pl and Ar	• high energy environment • alternating current strength • dominantly unidirectional current • low salinity as shown by the absence of bioturbation • fluvially influenced estuarine sandy point bar
F2c mud-dominated inclined heterolithic stratification	• gradational base • sharp to gradational top • commonly overlies on F2b, F2e • can up to 10 meters thick	• rare synaeresis cracks • double mud drapes • flaser and wavy bedding common • inclined to slightly inclined bedding • thinly laminated beds	• silt laminae • sand laminae • organic detritus • clay • grain size is very fine sand • well sorted • subangular to subrounded grains	• generally absent of bioturbation • rare Pl and Ar	• low to moderate energy environment • alternating current strength • low salinity as shown by the absence of bioturbation • fluvially influenced estuarine muddy point bar
F2d bioturbated mud-clast breccia in inclined sand	• lower contact sharp, or grades over 20 cm • may grade across 10-20 cm when over-lying F1a • commonly sits on F1a, F1b, F2a, F2b, and F2c	*Matrix* • planar tabular to inclined beds • breccia clast size 0.5mm to 1 meter dia. • rare current ripples • double mud drapes • flaser, wavy, and lenticular bedding	• rip-up clasts • rare organic detritus • consistent grain size • very well sorted • subangular to subrounded grains	• absent of bioturbation	• high energy environment • deposition in unidirectional currents • breccia clasts contain brackish signatures through trace fossil suites • estuarine bank-collapse-breccia • element of channel margin rip-ups • rapid emplacement
		Clasts • convolute bedding • thinly laminated bedding • massive bedding	• organic detritus	• low trace fossil abundance • low diversity Pl, Cy, Ar • low diversity horizons present	

Table 2.1. (cont).

Description	Occurrence / Contacts	Physical Structures	Texture and Lithologic Accessories	Ichnologic Characteristics	Interpretation
F2e sand-dominated burrowed inclined heterolithic stratification	• sharp to gradational base • gradational top • can up to 20 meters thick • commonly overlies F1a, F1b, F2a-d	• rare current ripples • rare climbing ripples • reactivation surfaces • double mud drapes • lenticular to wavy bedding • inclined to slightly inclined bedding • thinly laminated beds	• silt laminae • mud laminae • carbonaceous debris • rare wood fragments • rare rip-up clasts • grain size is medium sand • well sorted • subangular to subrounded grains	• low to moderate trace fossil abundance • low diversity Sk, Cy, Pl, Ar, Gy • monospecific assemblages • low diversity horizons	• high energy environment • alternating current strength • dominantly unidirectional current • brackish salinity as shown by the impoverished marine trace assemblage • estuarine sandy point bar
F2f mud-dominated burrowed inclined heterolithic stratification	• gradational base • sharp to gradational top • can up to 10 meters thick • commonly overlies F2a-e	• rare synaeresis cracks • double mud drapes • flaser and wavy bedding common • inclined to slightly inclined bedding • thinly laminated beds	• silt laminae • sand laminae • organic detritus • clay • grain size is very fine sand • well sorted • subangular to subrounded grains	• low to moderate trace fossil abundance • low diversity Sk, rare Cy, Pl, Gy, Ar • monospecific assemblages • low diversity horizons	• low to moderate energy environment • alternating current strength • brackish salinity as shown by the impoverished marine trace assemblage • estuarine muddy point bar
Facies 3 (F3) horizontally interbedded sand and mud					
F3a sand-dominated horizontally bedded interbedded sand and mud	• gradational base • sharp to gradational top • commonly overlies F2 • can be up to 4 meters thick • commonly intercalated with F1b, F3c and F3b	• rare current ripples and combined flow ripples • double mud drapes • flaser, wavy, and lenticular bedding • thinly laminated beds	• silt laminae • sand laminae • mud laminae • rare carbonaceous debris • grain size is very fine sand • well sorted • subrounded grains	• moderate trace fossil abundance • low diversity Sk, rare Cy, Pl, Gy, Ar • monospecific assemblages • dispecific assemblages • low diversity horizons • diminutive trace size	• moderate energy environment • alternating current strength • brackish salinity as shown by the impoverished marine trace assemblage • stressed tidal flat deposits that are sand dominated
F3b equally interbedded horizontally bedded sand and mud	• gradational base • scoured to gradational top • commonly overlies F2 and F3a • can be up to 5 meters thick • commonly intercalated with F1b, F3a, and F3c	• biogenic deformation • similar to F3a and F3c	• silt laminae • sand laminae • mud laminae • rare carbonaceous debris • grain size is very fine sand • well sorted • subrounded grains	• high trace fossil abundance • low diversity Sk, rare Cy, Pl, Gy, Ar • monospecific assemblages • low diversity horizons • diminutive traces	• low to moderate energy environment • alternating current strength • brackish salinity as shown by the impoverished marine trace assemblage • healthy tidal flat deposits of equally sand and mud
F3c mud-dominated horizontally bedded interbedded sand and mud	• gradational base • sharp to gradational top • commonly overlies F2 • can be up to 5 meters thick • commonly intercalated with F1b, F3a and F3b	• rare current ripples and combined flow ripples • double mud drapes • flaser, wavy, and lenticular bedding • thinly laminated beds	• silt laminae • sand laminae • mud laminae • rare carbonaceous debris • grain size is very fine sand • well sorted • subrounded grains	• moderate trace fossil abundance • low diversity Sk, rare Cy, Pl, Gy, Ar • monospecific assemblages • dispecific assemblages • low diversity horizons • diminutive trace size	• low energy environment • alternating current strength • brackish salinity as shown by the impoverished marine trace assemblage • stressed tidal flat deposits that are mud dominated

Table 2.1. (cont).

Description	Occurrence / Contacts	Physical Structures	Texture and Lithologic Accessories	Ichnologic Characteristics	Interpretation
F3d horizontally interbedded sand and mud with robust bioturbation	• gradational base • sharp to gradational top • commonly overlies F1c, F1d, F3a, F3b, and F3c • can be over 5 meters thick • commonly intercalated with F1d and F3e • can underly Wabiskaw Member	• oscillation ripples • common current ripples • climbing ripples • double mud drapes • flaser and wavy bedding common • thinly laminated bedding • combined flow ripples	• silt laminae • sand laminae • rare carbonaceous debris • grain size is very fine sand • well sorted • subrounded grains	• moderate trace fossil abundance • high diversity Pl, Pa, Di, Ro, Th, Te, As • robust trace size • proximal Cruziana ichnofacies	• low to moderate energy environment • alternating current strength • very marine salinity as shown by the robust marine trace assemblage • stressed bay deposits of high salinity that are colonized by marine fauna and are totally subaqueous
F3e pervasively churned sand and mud with robust bioturbation	• gradational base • scoured to gradational top • commonly overlies F1b, F1d, F3a-d • can be up to 5 meters thick • commonly intercalated with F1d and F3d • can underly Wabiskaw Member	• biogenic deformation • similar to F3d	• silt laminae • sand laminae • mud laminae • rare carbonaceous debris • grain size is very fine sand • well sorted • subrounded grains	• high trace fossil abundance • high diversity Pl, Pa, Di, Ro, Th, As • robust trace size • Skolithos ichnofacies	• low to moderate energy environment • alternating current strength • very marine salinity as shown by the robust marine trace assemblage • healthy open bay deposits of high salinity that are colonized by marine fauna and are totally subaqueous
Facies 4 (F4) horizontally bedded silts and muds					
F4a massive to laminated grey mud	• always gradational base • typically scoured top • variable thickness • commonly overlies F2c, F2f • commonly overlain by F4b	• synaeresis cracks common • rare flaser bedding • convolute bedding common • slightly inclined bedding • mottled bedding • massive bedding	• silt laminae • rare pyrite • rare organic laminae • organic detritus and incipient siderite-ation locally common • grain size is silt to clay • well sorted • subrounded grains	• low trace fossil abundance • low diversity Te, Pl, Gy (II) • low diversity horizons • pinstripe Gyrolithes (Gy II)	• low energy environment • brackish salinity indicators through trace fossils • laminations thin upwards indicating channel abandonment
F4b white silty mud	• gradational base • gradational to scoured top • commonly overlies F4a • commonly overlain by F4c or scoured into by F1a	• synaeresis cracks common • convolute bedding common • thinly laminated bedding • mottled bedding • massive bedding	• silt laminae • rare sand lenses • rare organic laminae • organic detritus and incipient siderite-ation locally common • rare pyrite • paleosol horizons common • grain size is silt to clay • very well sorted • subrounded grains	• low trace abundance • low diversity Pl, Te, • trace fossils were observed in one location only and in a thin silty bed of this facies • Rhizoliths	• low energy environment • white mud indicates subaerial exposure • rootlets indicate colonization by organic material • flood basin deposit
F4c dark grey carbonaceous mud with bedded coals	• sharp to gradational base • typically scoured top • commonly overlies F4b • commonly overlain by F1a or F1b	• rare flaser beds • thinly laminated bedding • massive beds • high clay content	• silt laminae • sand laminae • organic and coal laminae • organic detritus • coal beds up to 2 meters in thickness • paleosol horizons common • pyrite • grain size is silt to clay • very well sorted • subrounded grains	• absent of bioturbation • Rhizoliths	• low energy environment • well-vegetated environment • frequently scoured into by coarse-grained channels • flooding marsh paleosol in flood basin area

Table 2.1. (cont).

(<5cm) cross-stratified sand (F1c), and laminated to well-burrowed sand (F1d).

These facies are rarely found altogether in core and outcrop examples. The facies F1a, F1b, and F1c can intercalate with each other, as can examples of F1b, F1c, and F1d. Sedimentary examples of F1a and F1d were never observed to intercalate. These facies should be preferentially preserved due to the grain size of the sediments.

FACIES 1A (F1A) GRANULAR GRADING SANDS

Description:

Facies 1a is found throughout the lower part of the McMurray Formation in the study area and is also identified from midway through the complete vertical section. This facies is characterized by the overall coarse-grained nature of the sediment (Fig. 2.6). The sands of F1a range from pebble to fine-grained sand. The thickness of Facies 1a is variable from 25 centimeters to 4 meters and averages roughly 1 meter. Facies 1a comprises large-scale physical structures and has a relative paucity of lithologic accessories. Facies 1a can appear structureless when it is dominated by very coarse-grained sand. Typically the unit grades normally from a coarse granular lag layer at the base into low-angle, cross-stratified, upper fine-grained sand. This sub-facies generally repeats this grading over scour surfaces. Lags are commonly less than 10 centimeters thick, containing pebble grain size ranging up to 1cm in diameter. Mud breccia clasts appear in the lags as well as disseminated throughout the facies. Large carbonaceous debris and wood fragments are also common to this facies (Fig.2.6b). Core examples show minor sand and mud beds thinner than 3cm. Incipient siderite cementation is locally observed in finer-grained water-saturated sediments. Disseminated pyrite and concretions are abundant at the base of this facies, becoming less abundant with increasing facies thickness. Grains are typically angular to subangular and are poor to moderately sorted. Bioturbation is absent in F1a

The lower contact of F1a is scoured (Fig. 2.6a,d). It is commonly the facies

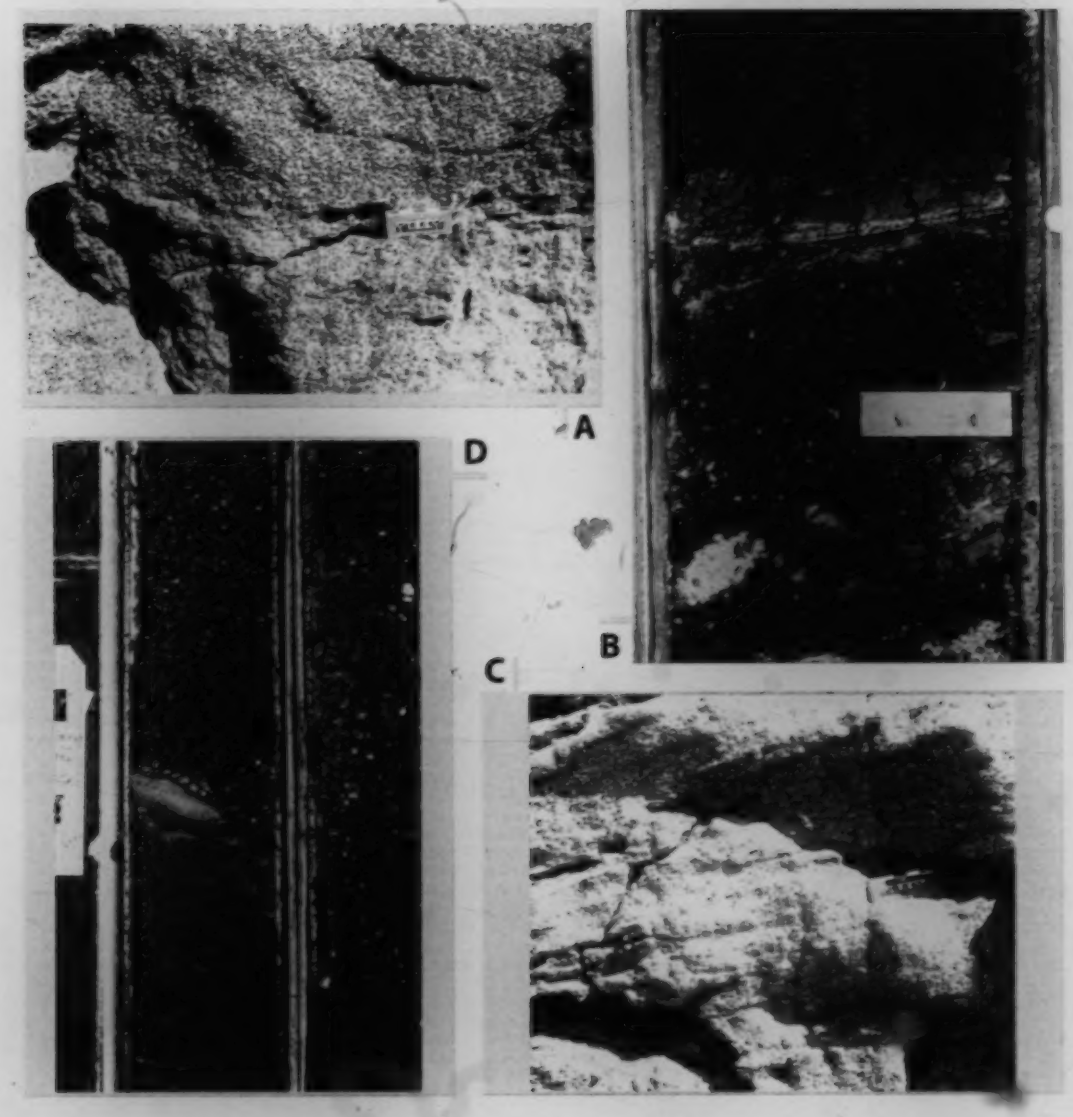


Fig. 2.6. Facies 1a. **A)** Facies 1a scoured into the underlying sediment at outcrop A1. **B)** Wood fragments (coal) and coarse-grained sand found near the base of core 12-26-95-11W4. **C)** Large-scale, coarse-grained cross-stratification found at outcrop E11. **D)** Scoured base of Facies 1a found in core 10-3-96-11W4 with coarse grains deposited over a medium grained sand.

observed above the Devonian unconformity surface in the study area. Facies 1a is also seen to scour into F4 muds and silts and F2 inclined heterolithics. The upper contact can be sharp to gradational into F1c small-scale cross-stratified sand, F1b high-angle cross-stratified sand, and F2 coarse-grained units. This facies is typically found in association with the Devonian unconformity surface, F4 muds, and F2 inclined beds.

Interpretation:

The deposits of F1a have been interpreted to represent deposition within fluvially dominated braided channels. The scoured base is diagnostic of an erosive high-energy environment. The granular sands grade upwards indicating a progressively lessening of depositional energy. Large-scale cross-stratification is the result of the development of shallow subaqueous bars. The absence of fines in this facies is due to the high-energy current that is interpreted to scour the channel, form the channel bars, and transport the pebbles and breccia clasts. Wood fragments and carbonaceous debris are incorporated into the sediment due to slack water conditions in post-flood channel conditions.

The lack of bioturbation indicates an environment too stressed for the colonization of burrowing organisms. This may be due to the high energy levels associated with braided channel systems or the low salinity levels found in a basal fluvially influenced channel succession.

FACIES 1B (F1B) HIGH-ANGLE CROSS-BEDDED SANDS

Description:

Facies 1b is found throughout the McMurray Formation in this area. This facies is characterized by high-angle cross-stratification of the sediment (Fig. 2.7). The subangular to subrounded sands of F1b range from medium- to upper fine-grained. Facies 1b manifests itself as stacked units of high-angle cross-stratified sand separated by master bedding

planes/reactivation surfaces that may or may not contain thin mud drapes and bioturbation. The thickness of the individual units in F1b is variable from 40 centimeters to 2.5 meters. The overall thickness of this facies can reach 4 meters. Facies 1b contains large-scale features such as planar-tabular to trough cross-stratified sands, and small-scale features such as current and rare climbing ripples. The high-angle stratified beds observed in outcrop display a sigmoidal base where they downlap onto the master bedding planes or reactivation surfaces (Fig. 2.7c). Bedding can appear thinly laminated due to silt and rare mud laminae. A key component of this facies are the back-flow/reverse-flow ripples that are rare in core but are abundant in outcrop. These ripples migrate back up the high-angle stratification and typically contain an upper fine-grained sand to fine silt grain size. Bed-sets in this facies do not display grading. This facies does however contain grain striping that manifests as thin beds of alternating grain size along cross-stratification surfaces. This occurs when there is an alternation between high and low current velocities. Facies 1b does not contain rip-up clasts, wood fragments, or coal laminae. Carbonaceous detritus may be present within fine-grained laminae on the high-angle cross-stratification and can be common at the base of the sigmoids. Core examples show minor unbioturbated mud beds along the master bedding planes (Fig. 2.7a) while several outcrop examples display monospecific *Cylindrichnus* assemblages along these planes due to the weathered viewing area and the enhanced preservation of the coarser-sand bodies in outcrop (Fig. 2.7b).

The lower contact of F1b is sharp. It commonly overlies F1a sands, F2b, F2c, F2e and F2f inclined heterolithics. The upper contact of F1b is sharp both between the internal units, and the overlying facies. Overlying facies include F1c small-scale cross-stratified sands, F1d laminated to well-burrowed sands, and F2 inclined heterolithics. This facies is commonly intercalated with F1c, and F2 facies.

Ichnology:

Bioturbation within facies 1b is limited and best identified in outcrop exposures.

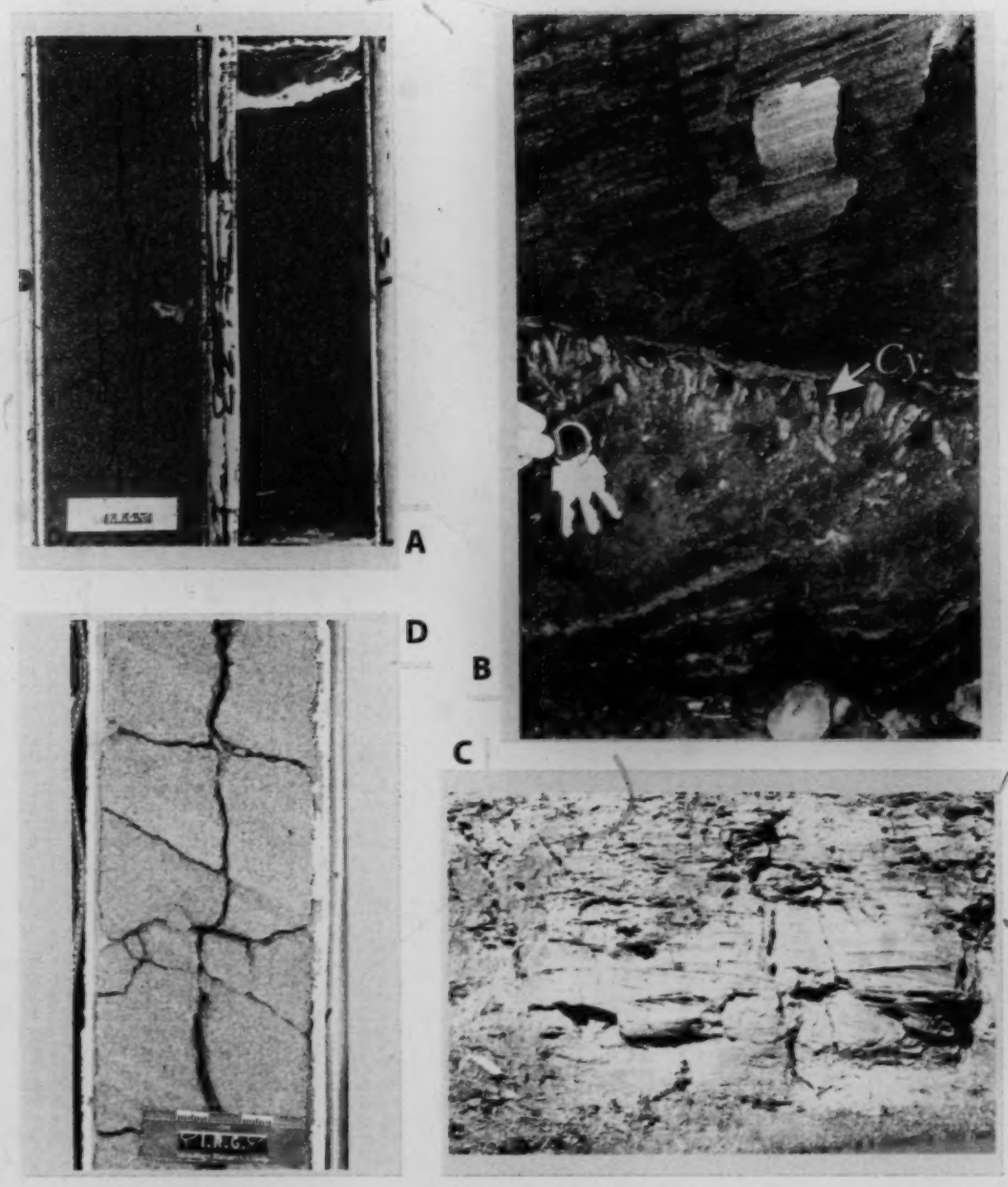


Fig. 2.7. Facies 1b. **A)** Inclined bedding found in well-saturated core in well 14-23-95-11W4 displaying unbioturbated mud beds at master bedding surfaces. **B)** Monospecific *Cylindrichnus* (Cy.) assemblage found at outcrop E5. **C)** The repeating nature of F1b observed in outcrop E5. **D)** Core surfaces from water saturated horizons (10-16-96-11W4) typically best display the internal detail of F1b.

The trace fossils are encountered in low abundances, with a low diversity of trace types. Bioturbation in this unit is absent or common on master bedding planes. *Skolithos*, a vertical trace, is rare but identified in core 11-3-96-11W4 and at outcrop E12. *Cylindrichnus*, a subvertical burrow, is noted in core examples as well as numerous outcrop examples. This behavior is indicative of a filter-feeding organism that lines the walls of its sand penetrating burrow with mud. It has been postulated by others (Bechtel, 1996; Beynon and Pemberton, 1992) but unproven by this study that the curving shaft of these organisms points in the direction of dominant flow. This trace occurs on master bedding planes between units, in monospecific assemblages of moderate abundance (Fig. 2.7b). In all examples, the overlying mud bed has been eroded and only the shafts of the trace are seen in the underlying sand (Fig. 2.7b).

Conichnus, the interpreted dwelling trace of sea anemones (Shinn, 1968; Pemberton, 1998), has been identified in outcrops E15 and A2. The large size of this trace makes it difficult to characterize in core. Sea anemones are marine- to marginal-marine organisms capable of living in mesohaline environments.

Interpretation:

The deposits of F1b have been interpreted to represent deposition and migration of shallow subaqueous bars by fluvial energy. The grain size, high-angle cross-stratification, and grain striping indicate a high-energy environment of lightly fluctuating current strength. The individual units in this facies indicate 2- or 3-dimensional bars by the presence of planar-tabular and trough cross-stratification. The presence of back-flow/reverse-flow ripples indicates that although the primary sediment transport was in one direction, there was an element of minor transport in the opposite direction (Allen, 1980). This subordinate tidal flow allowed ripples to migrate up the reactivation surfaces on the individual bar units (Visser, 1980; Dalrymple, 1992). Grain striping also gives evidence for a tidally influenced depositional environment (de Boer *et al*, 1989; Wightman and Pember-

ton, 1997; Arnott, 2001). The striping found in the foreset bundles may be a result of the unequal strength of current velocities in successive tides due to an unbalanced tidal range. The inferred height of the migrating subaqueous dunes (1-4m) indicates a water depth of at least 3-4 meters (Boggs, 1995). The lack of mud in this facies is due to the high-energy currents that consistently erode the finer grained tops of the individual migrating bar units. The large scale cross-stratification observed in F1b has been identified as a common and significant feature of fluvial to estuarine sand bodies (Boersma and Terwindt, 1981; Reinson, 1992; Yang and Nio, 1989).

Bioturbation is rare to locally common on the reactivation surfaces representing the eroded tops of individual migrating bars. The overall abundance and low diversity of trace types indicates a stressed physico-chemical environment that only opportunistic organisms can colonize with minor success (Allen, 1980). *Skolithos* and *Cylindrichnus* are common brackish water traces and the overall number of noted surfaces colonized by these opportunistic behaviors is expected to increase with marine influence (Pemberton and Wightman, 1995). The trace fossil *Conichnus* does not occur in oligohaline conditions such as strictly fluvial systems. The occurrence of this trace in F1b indicates an environment of deposition in more marine waters than the fluvial channel environment of F1a. The presence of *Conichnus* therefore suggests a transition from fluvially dominated channels to more marine estuarine channels.

FACIES 1C (F1C) SMALL-SCALE CROSS-STRATIFIED SANDS

Description:

Facies 1c is found throughout the McMurray Formation in the study area. This facies is characterized by small-scale cross-stratified sand (Fig. 2.8). The subangular to subrounded sand grains of F1c range from medium to upper very fine. Facies 1c typically occurs as thin (5cm) sets of cross-laminae that may or may not be separated by a thin mud.

Similar sedimentary structures can be found in other facies, but F1c is classified as being exclusively small-scale cross-stratified sand over a significant interval. The overall thickness of this facies can reach 2 meters. As noted by Bechtel (1996) in his 'small-scale cross-stratified sand' facies, the nature of the stratification is dependant on the orientation of the slabbed surface of the core. As a result Facies 1c contains apparent large-scale features such as planar tabular to trough cross-stratified sands, and small-scale features such as current and climbing ripples (Fig. 2.8a). Tabular appearing sands are planar cross-stratified with sub-parallel bounding surfaces. Trough-shaped forms contain truncated upper surfaces (Fig. 2.8c) with a concave appearing base. Cross-strata generally parallel the lower bounding surface which can be a reactivation surface. Facies 1c does not contain rip-up clasts, wood fragments, or coal laminae. Carbonaceous detritus may be present within the fine-grained laminations. Core examples show thin (<1cm) unbioturbated mud beds along the bounding surfaces (Fig. 2.8). Sideritization and/or pyrite is not common in this facies.

The lower contact of F1c is typically sharp unless it is overlying F1a or F1b. It commonly overlies F1a, F1b, Facies Group 2 sandy IHS, and Facies Group 3 horizontal interbeds (Table 2.1). The upper contact of F1c is sharp both between the internal units, and the overlying facies. Overlying facies include F2 inclined heterolithics and F3 horizontal interbeds. This facies is commonly intercalated with F3a and F3b.

Ichnology:

Facies 1c has limited bioturbation best identified through outcrop exposures due to weathering of the exposed surface. The trace fossils are encountered in low abundances with a low diversity. Bioturbation in this unit can be rare or common on master bounding surfaces and is dependant on the amount of underlying material eroded prior to deposition of the later sediment. *Skolithos*, *Cylindrichnus*, and escape traces (fugichnia) can be present. The internal laminations of the small-scale cross-stratified sand contains only escape traces (Fig. 2.8c). *Skolithos* and *Cylindrichnus* traces occur on bounding surfaces between

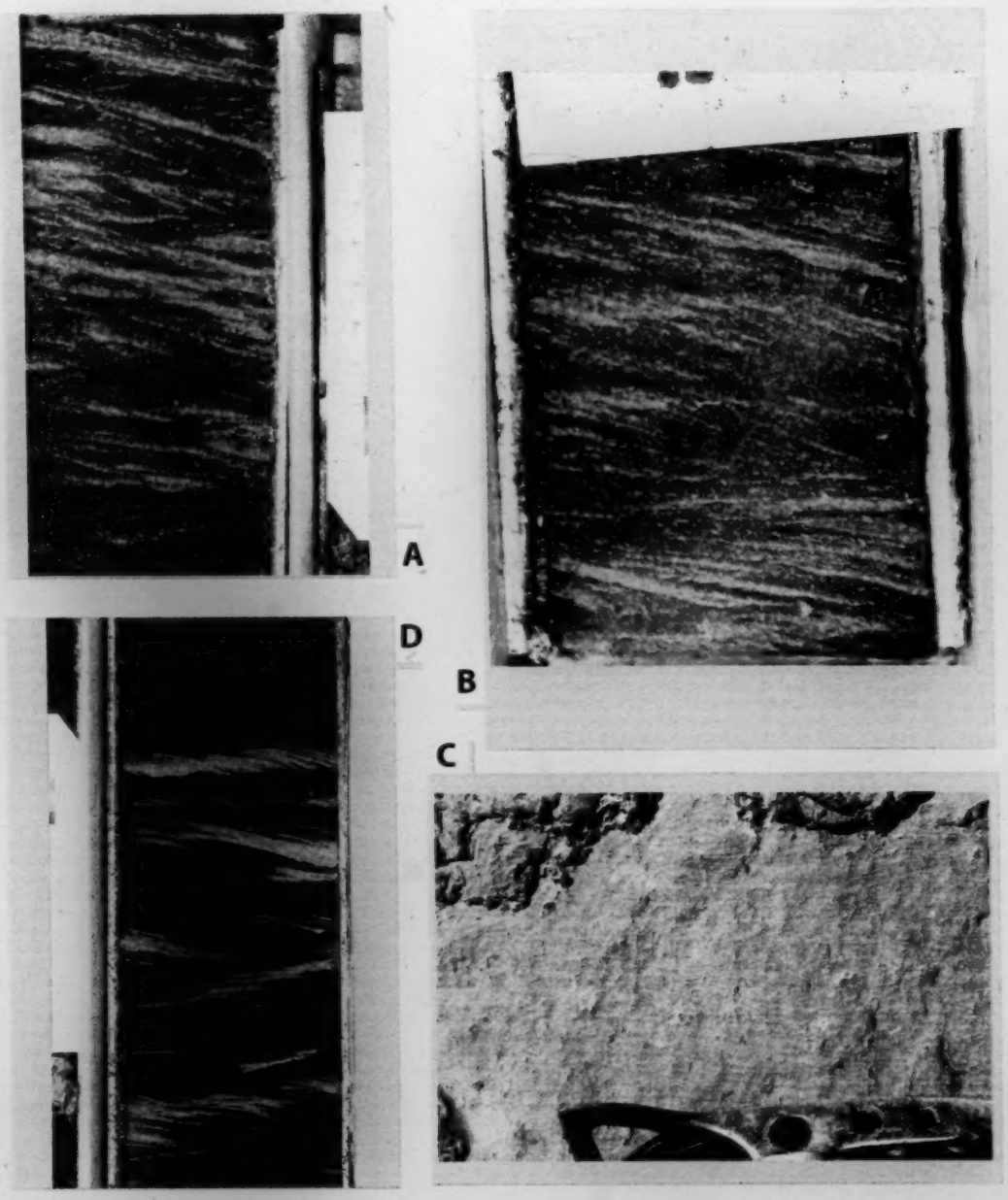


Fig. 2.8. Facies 1c. **A)** Small-scale cross-stratification observed in core appears complex due to the nature of the slabbed surface (AB/10-20-96-11W4). **B)** Current and climbing ripples are the dominant structures in F1c (AB/10-20-96-11W4). **C)** Outcrop examples display oscillatory ripples and give indications of bioturbation (E12). **D)** Small-scale current ripple laminations in core (10-8-96-11W4).

bed-sets in monospecific assemblages of moderate abundance. In many examples, the overlying mud bed has been eroded and only the shafts of the trace are seen in the underlying sand. The escape traces occur in the thicker bed-sets due to rapid sedimentation, and have only been identified in outcrop due to the visibility of this trace from outcrop weathering related water washing.

Interpretation:

Facies 1c is interpreted to be the result of deposition from one of two processes: 1) waning flow conditions on larger-scale channel bedforms and 2) higher flow conditions such as run-off channels on tidal flats. Small-scale cross-stratification is the result of ripple migration and can be termed ripple bedding (Harms and Fahnestock, 1965; Boggs, 1995). Apparent tabular-shaped sets of ripples are due to viewing the ripples in a section parallel to flow direction. Trough shaped sets result from viewing the ripples perpendicular to the overall flow and migration direction.

Small-scale cross-stratification can be produced by current flow or wave action. Dominantly current produced cross-stratification is interpreted to be deposited in channels while dominantly wave produced cross-stratification is interpreted to represent deposition on the surface of inundated tidal flats. The rippled bedding found in outcrops and core in the study area lacks the features of oscillation wave ripples as described by Reineck and Singh (1980) and Southard *et al.* (1990) with the exception of thin intervals in sand-dominated tidal flats. The bedding in F1c is therefore interpreted to be the result of direct current flow or the interaction of current and wave action to produce combined flow. Current ripples dominate the observed structures with the rare appearance of combined flow ripples. Combined flow ripples are the result of; the migration of a wave ripple due to the introduction of current flow, or imposition of oscillation forces on a current ripple (Inman and Bowen, 1963; Harms *et al.*, 1982; Murray *et al.*, 1991). The fluctuating character of the flow responsible for combined flow ripples is consistent with the tidal processes associ-

ated with estuarine conditions. Quiescent water conditions allow for the development of waves in slack tidal periods. Climbing ripple cross-lamination can then represent waning flow conditions as abundant sediment held in suspension is deposited in this lower flow regime structure (de Boer *et al.*, 1989).

Small-scale cross-stratification forms at the lower end of the lower flow regime (Harms and Fahnestock, 1965; Guy *et al.*, 1966; Boggs, 1995). During lower velocity flow conditions associated with the beginning or end of the slack water component of the tidal cycle, smaller scale bedforms develop on the surface of larger bedforms (Reineck and Singh, 1980). These conditions may also develop as the result of falling water levels during ebb tide. Small scale cross-stratification may also form during high tide cycles or episodic events where flood tide has inundated the tidal flat environment. The mud laminae on bounding surfaces are another indication of fluctuating flow conditions as suspension deposition of mud from slack water (Visser, 1980).

Facies 1c has a trace fossil assemblage similar to F1b. This reflects the unstable, shifting nature of the substrate. Escape traces verify the periodic high deposition rates and shifting bedform nature associated with this environment. The rare low diversity assemblages in this environment coincide with the appearance of combined flow ripples due to wave action. These sediments are interpreted to be deposited on the surface of the tidal flat, where many types of organisms live and feed (Dorjes and Howard, 1975). The opportunistic trace fossil assemblage, represented by vertical burrows of suspension feeders, indicates the rapid deposition and high degree of physical reworking associated with these deposits. The diminutive, low diversity, and stressed assemblage present in this facies represents deposition in brackish water conditions (Pemberton and Wightman, 1992; Wightman and Pemberton, 1997). Accumulations of F1c can be devoid of bioturbation. These deposits are dominantly current-rippled and are interpreted to represent waning flow conditions on a larger channel bedform, or moderate energy conditions in a small run-off channel.

FACIES 1D (F1D) LAMINATED TO WELL-BURROWED SAND

Description:

Facies 1d is found mainly in the upper sections of the McMurray Formation in the study area. This facies is characterized by fine-grained sand intercalated with zones of high bioturbation (Fig. 2.9). The well-sorted sands of F1b range from lower very fine- to upper fine-grained. Grains are typically rounded to subrounded. Facies 1d manifests itself as stacked successions of sharp-based thinly laminated to thinly bedded sands gradationally passing into well-burrowed siltier sands of unpredictable thickness. The thickness of the individual units in F1d is variable from 5 centimeters to 30 centimeters. The overall thickness of this facies can reach 4 meters. The sand of F1d typically contains undulatory, low-angle wavy planar laminated to ripple cross-laminated sand. Carbonaceous laminae are locally present and define bedding planes. Bedding can appear thinly laminated due to silt and rare mud laminae.

The lower contact of F1d is typically sharp. It commonly overlies F3a, F3b, and F3c facies, and is intercalated with F3d and F3e. The upper contact of F1d is sharp both between the internal laminated-bioturbated sets, and the overlying facies. Overlying facies include F3d and F3e horizontal interbeds and the Wabiskaw member of the Clearwater Formation.

Ichnology:

Facies 1d has robust bioturbation best identified from core where preservation is better and more vertically extensive. The trace fossils are encountered in moderate abundances, generally separated by the laminated layers. The trace fossil types of F1d are highly diverse and include: *Skolithos*, *Rosselia*, *Diplocraterion*, *Planolites*, *Palaeophycus*, *Thalassinoides*, *Teichichnus*, and *Scolicia*. These traces appear in high diversity assemblages throughout the sediment. The overall size of the trace fossils is large (greater than 2

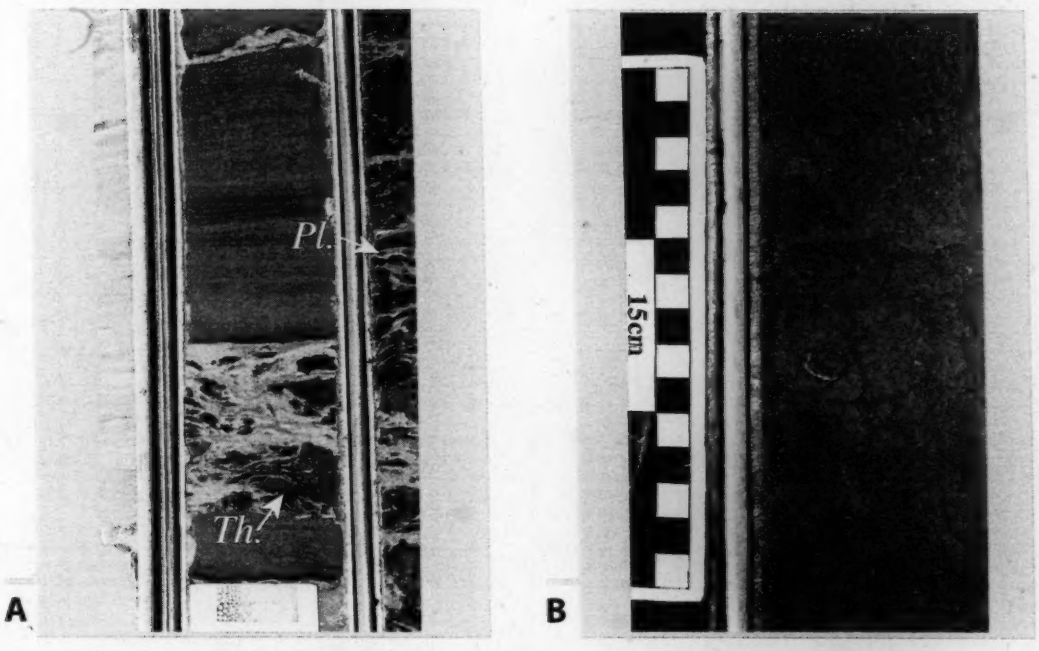


Fig. 2.9. Facies 1d. **A)** silty mud with a high degree of bioturbation separates the sandy laminated intervals (12-21-96-11W4). **B)** burrowed sand from facies 1d. The sand has no vestigial laminations visible over this interval (15-9-96-11W4).

cm in diameter). Escape traces are common in the outcrop example of the laminated sand component.

Rosselia appears as a ball-shaped trace tapering downwards into a curving *Cylindrichnus*-like shaft. The burrow is actively lined with mud including the ball that is concentrically laminated. *Diplocraterion* is a behavior characterized by an open u-shaped tube inhabited by various organisms. *Palaeophycus* is a sediment mining behavior characterized by a circular burrow with a mud lining. *Thalassinoides* is a horizontal, circular, branching burrow. In modern deposits, these burrows are inhabited by shrimp (Gingras *et al.*, 1999a). The *Thalassinoides* burrow diameter in this facies is far larger (>2cm) than the *Planolites* burrows encountered in this and other facies (Fig. 2.9a). *Teichichnus* is an unlined vertical trace with remnant internal laminae (spreiten). *Scolicia* is a burrow characterized by unevenly developed, concentric-shaped spreiten. This burrow is rare and often confused

with the trace fossil *Asterosoma* which is not present.

Interpretation:

The deposits of F1d have been interpreted to represent deposition and migration of shallow marine sand bodies. The grain size, sorting, and alternating high-energy/low-energy bedding indicate deposition in a moderate to high-energy environment. There is variation in marine sand deposits. This makes identification of a particular sand body very difficult. Storm deposits, scour events, fluctuating tidal energies, and periodic exposure can modify these sands. When seen in outcrop, it is obvious that the parallel laminated sands of F1d comprise a larger bedform whose overall shape is elusive due to reworking.

The episodic nature of the bioturbation and lamination in F1d indicates episodic event deposition. Burrowing is limited to the upper beds and laminae of the laminated sand in these laminated to burrowed bed-sets. The trace fossil assemblage therefore represents colonization between episodes by opportunistic organisms with subsequent burrowing by the resident equilibrium population. *Skolithos* and *Planolites* burrows are interpreted to represent the activities of opportunistic organisms and are characterized by morphologically simple forms. The equilibrium suite represents more robust dwelling structures erected by equilibrium organisms. These include: *Rosselia*, *Diplocraterion*, *Scolicia*, *Palaeophycus*, *Skolithos*, *Teichichnus*, and *Thalassinoides*. The burrowed zones indicate areas where the equilibrium population is attempting to re-establish itself. The burrows present in the equilibrium suite crosscut those of the opportunistic suite. The equilibrium suite is characteristic of the mixed *Skolithos/Cruziana* assemblage identified as representative of brackish waters with a notable inclination towards being dominated by the *Skolithos* assemblage of more marine waters (Pemberton *et al.*, 2001; Bechtel *et al.*, 1994). The trace fossil assemblage of F1d is more diverse than that of F1c and therefore represents a more marine influence as a greater diversity of organisms can inhabit conditions of increased salinity. Escape traces are seen at the outcrop scale to extend through laminated zones into

the overlying bioturbated zones. This reflects the organism's movement through the rapidly deposited event bed to establish itself at the sediment water interface during the subsequent fair-weather conditions (Pemberton, 1998). This type of laminated to burrowed bedding is interpreted to represent episodic storm deposition.

FACIES 2 (F2) INCLINED HETEROLITHIC SEDIMENTS

Several subfacies found in sediments of the McMurray Fm. display inclined bedding. These subfacies are found mainly throughout the lower and middle sections of the McMurray Fm. The facies group is made up of six subfacies: mud-clast breccia in inclined sand (F2a), sand-dominated Inclined Heterolithic Stratification (IHS) (F2b), mud-dominated inclined heterolithic stratification (F2c), bioturbated breccia in inclined sand (F2d), sand-dominated burrowed inclined heterolithic stratification (F2e), and mud-dominated burrowed inclined heterolithic stratification (F2f)(Table 2.1).

These subfacies are often found together in many core and outcrop examples. The subfacies of F2 intercalate with each other as well as with certain subfacies of Facies 1, Facies 3, and Facies 4.

FACIES 2A (F2A) MUD-CLAST BRECCIA IN INCLINED SAND

Description:

Facies 2a is defined by inclined sand containing abundant rip-up clasts (Fig. 2.10). This facies is common in the lower to middle sections of the McMurray Formation in the study area. This unit can range in thickness from less than one meter to three meters in thickness. The visible degree of inclination of the strata in core is dependant upon the angle at which the core was slabbed. Higher angles are associated with slabs paralleling depositional dip; lower angles are associated with slabs paralleling depositional strike. The

inclination angles of this facies in slabbed core and exposed outcrop range from 0-15°. Core views are two dimensional due to the PVC pipe slabs allowing viewing of only one cut through the core. The large-scale physical structures present in this facies are planar-tabular to inclined beds while small-scale structures such as current ripples are seen in unsaturated core. The grain size of this facies is medium- to fine-grained sand that is predominantly well- to very well-sorted. There is very little carbonaceous detritus found in F2a. This facies has internal scour surfaces and reactivation surfaces. There is no bioturbation present in the matrix of this facies (Fig. 2.10b).

The rip-up clasts of F2a are mud. These clasts range in size from 0.5 cm up to 15 cm in diameter. The clasts are generally massive mud although some clasts show thin laminations. Clasts in F2a are angular to subangular (Fig. 2.10d). The clasts parallel the bedding planes with the long axis of their shape (Fig. 2.10b). The clasts of F2a show very little tidal indicators such as flaser bedding and double mud drapes. They also do not show any biogenic structures.

Facies 2a commonly has an abrupt or scoured basal contact. It typically overlies F1a, F1b, F1c, and F2b. This facies is routinely intercalated with all other sandy F2 facies. Generally this facies is gradationally overlain by F2b or F2e.

Interpretation:

Breccia in inclined sand is interpreted to represent channel deposits associated with laterally accreting point bars of a meandering fluvial to estuarine channel. Sorting and grain size point towards a high-energy fluvial environment. The inclined beds are interpreted to be epsilon cross-stratified lateral accretion deposits formed by point bars (Reineck, 1958; Allen, 1963; Thomas *et al.*, 1987). These deposits form from the channel-ward migration of point bars in a meandering fluvial environment (Thomas *et al.*, 1987).

The angular character of the clasts indicate little to no transport from the source beds (Smith, 1972). This is consistent with inner-bar rip-ups and bank collapse breccias (Pro-

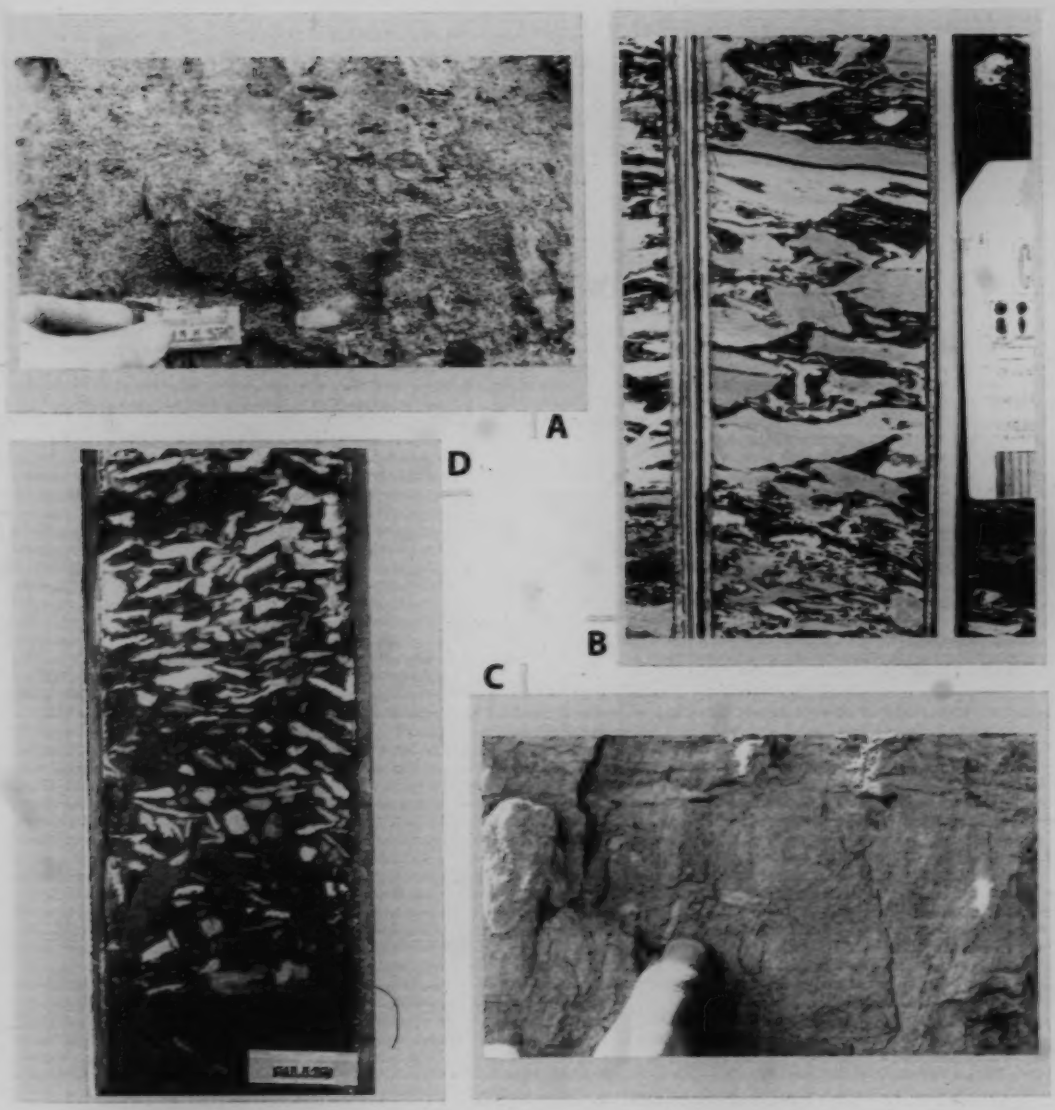


Fig. 2.10. Facies 2a. **A)** Exposure of F2a from outcrop A2. **B)** Dense, poorly sorted breccia from core 11-3-96-11W4. The long axis of the larger and more angular clasts parallel the depositional dip. **C)** Small examples of inner-bar breccia clasts from outcrop E12. **D)** small unbioturbated mud rip-ups exposed in core 15-9-96-11W4.

thero and Schwab, 1996). Changes in current velocity entrain mud eroded from the inside of the point bar as inner-bar rip-ups. The mud clasts ultimately accumulate in the channel thalweg due to suspension deposition (Fig. 2.11). Bank collapse breccia is also common as the meanders incise into the outer edge of the meander loop, causing bank slope failure and the introduction of large clasts of bank material into the channel thalweg (Fig. 2.11).

The mud clasts show no bioturbation or tidal indicators. This indicates that the eroded and re-deposited bank material was experiencing insignificant brackish conditions and no tidal influence.

To summarize F2a, it is evident from the physical structures that this facies was deposited in a meandering channel environment characterized by high-energy depositional conditions. Most likely, these strata accumulated as part of the deep channel equivalent of laterally accreting point bars in a meandering fluvially-dominated estuarine channel.

FACIES 2B (F2B) SAND-DOMINATED INCLINED HETEROLITHIC STRATIFICATION

Description:

Facies 2b is characterized by inclined, thickly interbedded and finely interlaminated sand and mud (Fig. 2.12). This facies is more common in the lower to middle sections of the McMurray Formation in the study area than in the upper sediments. The inclination angles of this facies in slabbed core and exposed outcrop range from 0-20°. This facies is described using the term "inclined heterolithic stratification" (IHS) as put forth by Thomas *et al* (1987) to replace the term "epsilon cross-stratification" of Allen (1963). Sand-dominated IHS is an end member of the continuum spectrum that has mud-dominated IHS at the opposing side. IHS is termed sand-dominated if the sand percentage in the unit comprises greater than 50% of the facies. This facies has internal scour surfaces and reactivation surfaces where distinct changes in the mud/sand ratio and contacts are vis-

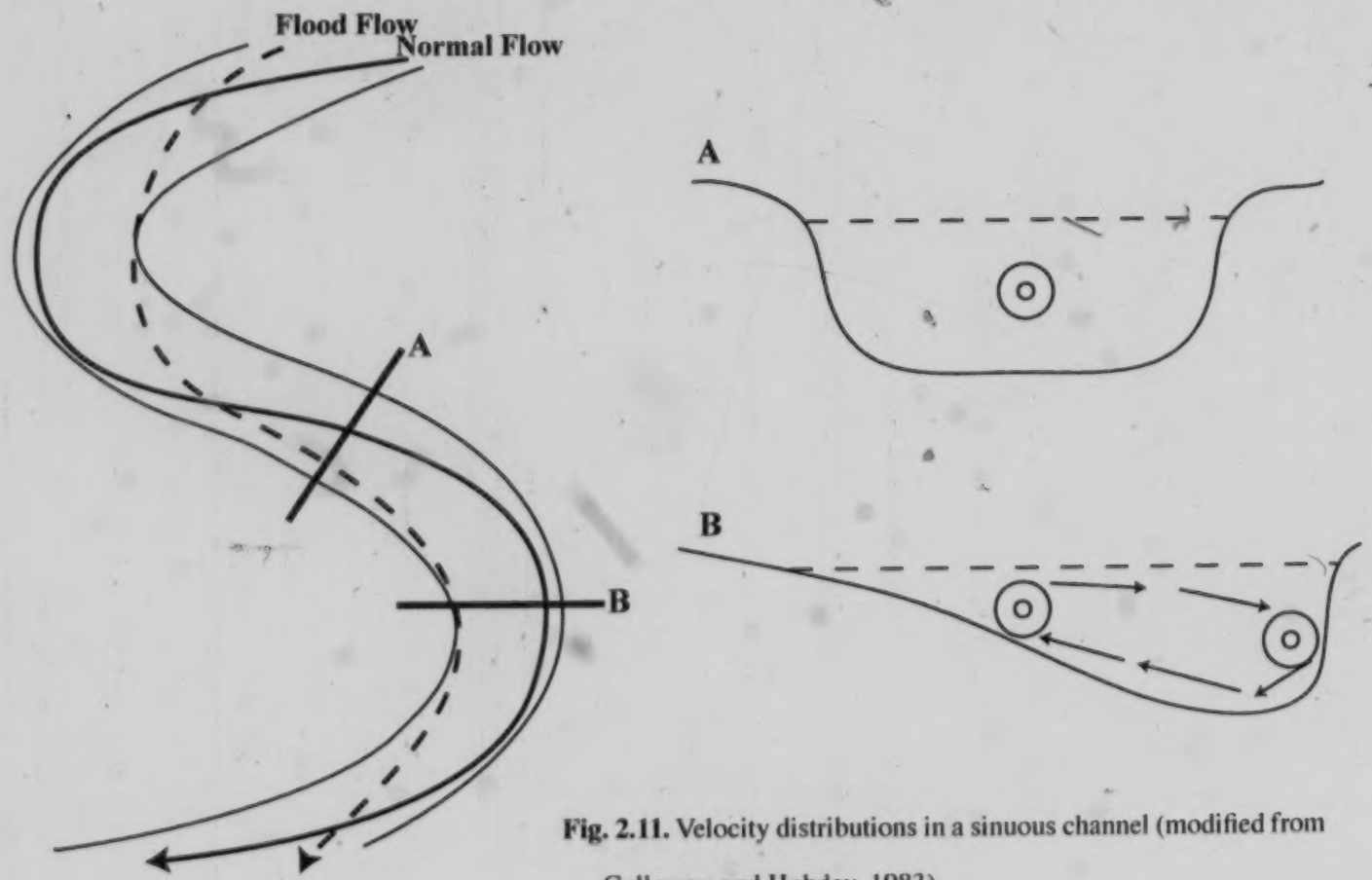


Fig. 2.11. Velocity distributions in a sinuous channel (modified from Galloway and Hobday, 1983).

ible.

The interbeds in this facies are medium- to thickly-bedded sand and mud where graded couplets define each interbed set. These graded couplets are sharp-based sand grading into or passing abruptly into overlying mud or interlaminated sand and mud layers (Fig. 2.12d). Contacts below and above these couplets are generally unburrowed although the upper parts of this facies may contain rare and diminutive burrows. Sand interbeds range from 5 cm to over 50 cm in thickness but average 10 cm (Fig. 2.12a). Mud bed thickness is generally thinner with a range of 1-20 cm and an average thickness of roughly 3 cm. Synaeresis cracks are rare and limited to the upper surface of thick mud beds.

The sand layers of the interbeds typically contain small-scale cross-stratified medium- to very fine-grained sands. The internal structure of these coarse beds display silt and mud laminae in wavy to lenticular style bedding. Current and climbing ripples as well as low-angle to flat planar stratification are all present. The coarse layers also can contain rare carbonaceous debris (Fig 2.12b). Weathered outcrop exposures show the most detailed internal geometry of the coarse units due to the decreased bitumen content from rainwater washing. Figure 2.12 shows the internal geometry of an exposure of F2b from outcrop. The thinly bedded laminae show silt and mud layers as wavy and lenticular bedding.

The fine layer of the couplet is defined by a mud that can be interlaminated with fine sand or silt. The muds are typically 5 to 10 centimeters thick. Interlaminated muds contain flaser to wavy style beds. Bioturbation in this facies is absent to rare.

Facies 2b has gradational upper and lower contacts although sharp contacts are present in various locations. The facies typically overlies granular sand (F1a), high-angle cross-stratified sand (F1b), small-scale cross-stratified sand (F1c), brecciated mudstones in inclined sand (F2a), burrowed sand-dominated IHS (F2e), and is typically intercalated with burrowed and unburrowed mud-dominated IHS (F2c, F2f). This facies can measure up to 20 meters thick.

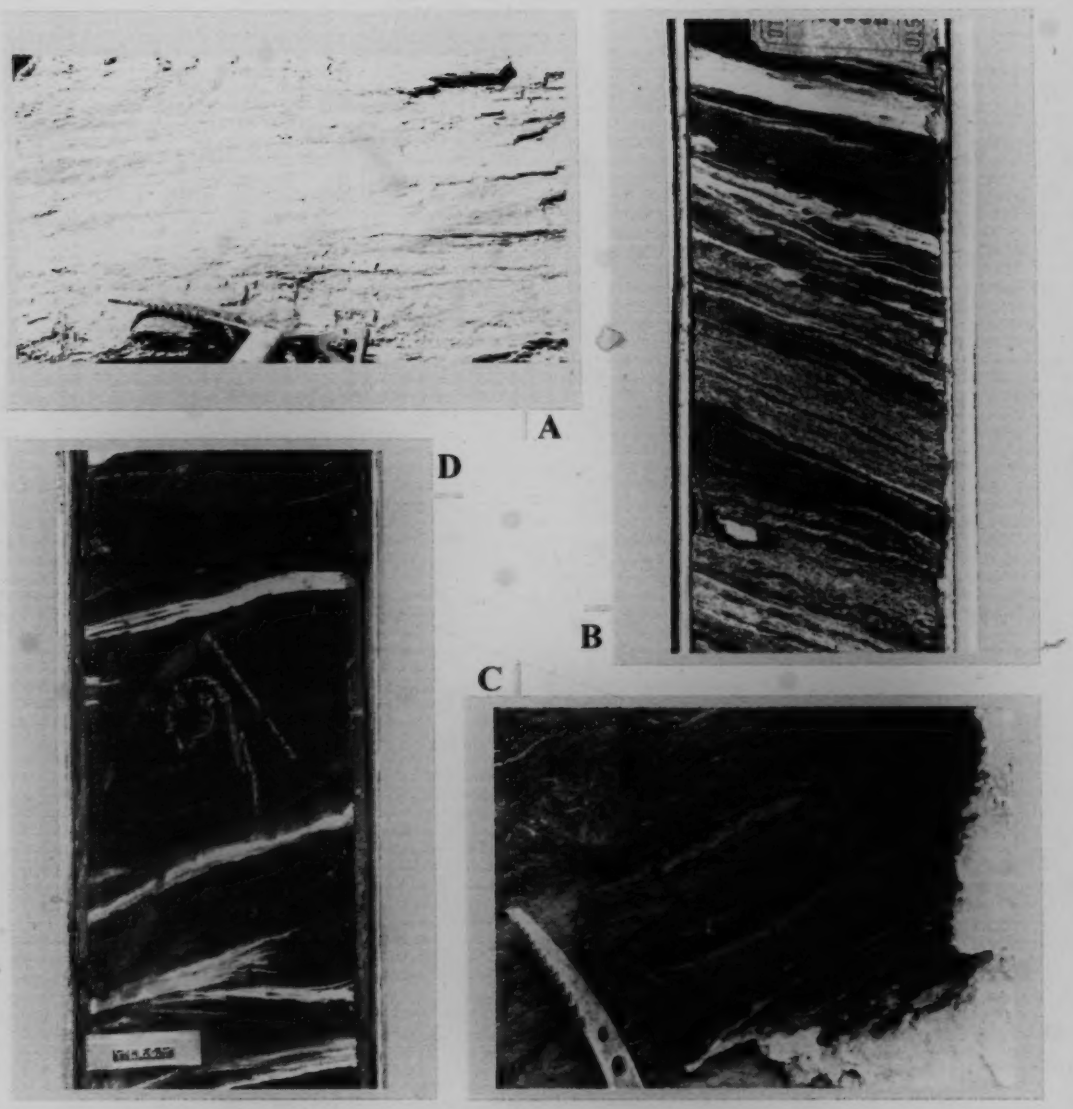


Fig. 2.12. Facies 2b. **A)** Outcrop exposure at E15 demonnstrating slightly inclined heterolithic bedding. **B)** Fine-grained carbonaceous material deposited along bedding planes (11-14-95-11W4). **C)** The internal geometry of the bedding of F2b is readily identifiable in outcrop. **D)** thin interbeds of mud over thicker sand intervals (11-3-96-11W4).

Ichnology:

The facies is most commonly unbioturbated but rare sections at the top of the facies may contain diminutive *Planolites* and *Arenicolites* traces. These simple burrows represent living and mining structures generated by small organisms attempting to establish themselves in this highly stressful environment. Traces were found in low abundance in this facies in very few core and outcrop examples.

Interpretation:

Facies 2b is interpreted to represent lateral accretion deposits associated with tidally influenced point bars in a meandering fluvial to estuarine channel. The cyclic nature of the bedding represented by the distinct coarser- and finer-grained beds indicate alternation in depositional conditions (Smith, 1988b). This is a distinctive feature of this facies. The coarse layer of the couplets is interpreted to be deposited under traction bedload deposition under higher flow velocities, while the fine layer is interpreted as deposition from suspension during periods of lower flow velocities such as at the beginning and end of flood and ebb tides. Alternately, it has been proposed that seasonal changes in fluvial discharge and tidal energy can create IHS sediments (Gingras *et al.* 1998; Eberth 1996; Lavigne, 1999). The interbedded sets described here are most likely deposited under seasonal changes related to river discharge. Sedimentary structures observed in the coarse layer indicate deposition under lower flow regime conditions, generating bedforms such as current and climbing ripples (Reineck and Singh, 1980). Occasionally upper flow regime conditions result in the development of planar stratification in the sandy layer. The sandy layer displays tidal signatures expressed as the alternating fine sand and silt or mud interlaminae that develops into wavy to lenticular bedding. Fluctuations in the local flow conditions are expressed in the character of the contacts between the coarse and fine layers. Sharp transitions indicate rapid flow changes including erosion of the underlying fine layer. Gradational contacts indicate gradual changes in flow velocity.

IHS bedding has been interpreted as the result of deposition on the inclined surface of a point bar within a meandering channel (Thomas *et al.*, 1987; Smith 1988a; Rahmani, 1988; Gingras, 1999). A defining feature of this facies is the cyclic nature of the interbeds and rhythmic character of the coarse layer interlaminae. It is now a well-held belief that cyclicity in tidal deposits is a diagnostic characteristic (de Raaf and Boersma; 1971; de Boer *et al.*, 1989; Nio and Yang, 1991). The rhythmic alternation of grain size itself indicates the fluctuating nature of the flow velocity. Due to the nature of grain suspension and traction, sand laminae were deposited under flood and ebb tidal conditions, while mud laminae were deposited under the associated slack currents at the start and end of the tidal cycles. Sand laminae and mud laminae sets can be deposited under a single tidal cycle (Fox, 1988). The thicker sand and mud beds are more difficult to classify as deposition within a single tidal cycle. It is more likely that these thicker deposits indicate a seasonal cycle where higher and lower flow velocities occurred for longer periods of time (Clifton and Phillips, 1973; de Mowbray, 1983; Lavigne 1999). Not all IHS deposits are created equal and while being indicative of tidal influence, they cannot be absolutely taken as an expression of diurnal cycles (Lavigne, 1999).

The concept that tide-dominated systems deposit only sediment that has both tidal influence and brackish signatures is incorrect as this facies shows a relative paucity of trace fossils yet abundant tidal signatures. This can be explained by the physiographic configuration of the hinterland (Lavigne, 1999). Depositional slope along the McMurray subbasin was very shallow, translating to extensive tidal prisms for even microtidal estuaries. Tidal backwater effects can extend well beyond the limits of the landward extension of the salt wedge (Allen, 1991; Lavigne, 1999). The 'freshwater tides' are capable of generating sedimentary structures indicating tidal influence despite being deposited in freshwater. In the upper Gironde Estuary located in France, Allen (1991) noted that tidal current reversals were felt roughly 50 kilometers upstream of the salt intrusion. These deposits represent tidal processes without expressing marine chemistries, making it impossible to separate the

effects of salinity and sedimentation rates. Bioturbation therefore becomes an indicator of salinity related to the salt wedge location (Lavigne, 1999).

Small rip-up clasts are common in estuarine channel deposits. These can be considered similar to the larger and thicker breccias encountered in F2a. The angular nature of these small rip-ups and their occurrence in thin horizons indicate short transport distances. Carbonaceous debris is also an expected lithologic accessory in this environment of deposition. Bordering the channels are areas of high organic content on banks, splay channels, and abandoned oxbows. The channel may cut into this material, entraining organic debris to be deposited along the bedding planes. Traceable coal laminae and beds are not features of this facies due to erosion and diffusion of this material.

The rare occurrence of synaeresis cracks indicate that upper sediments of F2b endured limited brackish influence. Burst (1965) and Plummer and Gostin (1981) showed that synaeresis cracks form in association with changes in salinity levels. These salinity fluctuations are common in estuaries due to the mixing of marine and fluvial waters. The rare appearance of *Planolites* and *Arenicolites* in this facies gives evidence to the development of more marine water chemistries towards the very top of the facies. The organisms responsible for these traces require near brackish water salinities to flourish. The rare appearance of these traces at the top of the facies indicates that conditions were becoming more amenable to organisms through increased salinity as time passed.

To summarize F2b, it is evident from the physical structures that this facies was deposited in a meandering channel environment characterized by dynamic depositional conditions. These strata accumulated as laterally accreting point bars in a meandering fluvially-dominated estuarine channel.

FACIES 2C (F2C) MUD-DOMINATED INCLINED HETEROLITHIC STRATIFICATION

Description:

Facies 2c is characterized by inclined, thickly interbedded and finely interlaminated mud and sand (Fig. 2.13). This facies is more common in the lower to middle sections of the McMurray Formation in this area. IHS is termed mud-dominated if the mud percentage in the unit comprises greater than 50% of the facies. Facies 2c is the end member of the continuum that has sand-dominated IHS as its counterpart. The inclination angles of this facies in slabbed core and exposed outcrop range from 0-15°. This facies has internal scour surfaces and reactivation surfaces where distinct changes in the mud/sand ratio and contacts are visible (Fig. 2.13d).

Like sand-dominated IHS (F2b), the interbeds in this facies are medium- to thickly-bedded mud and sand where graded couplets define each interbed set. Laminae of fine sand and mud are present throughout each couplet. The interlaminated couplets appear to normally grade from sand to mud and contain flaser style bedding. The thick graded bed-sets are sharp-based sand grading into or passing abruptly into overlying mud or interlaminated sand and mud layers. Contacts below and above these couplets are also relatively unburrowed. Sand interbeds range from 1 cm to 25 cm in thickness but average 5 cm. Mud bed thickness is generally thicker with a range of 1-50 cm and an average thickness of roughly 10 cm. Synaeresis cracks are rare.

The coarse layers of the interbeds typically contain small-scale cross-stratified fine- to very fine-grained sands defined by the interlaminae similar to F2b. Current and climbing ripples as well as low-angle to flat planar stratification are visible. The coarse layers also can contain carbonaceous debris although the size of the detritus is more diminutive than F2b. The fine layer of the couplet is defined by mud that can be interlaminated with fine sand or silt. The muds are typically 5 to 10 centimeters and contain a higher clay percent-

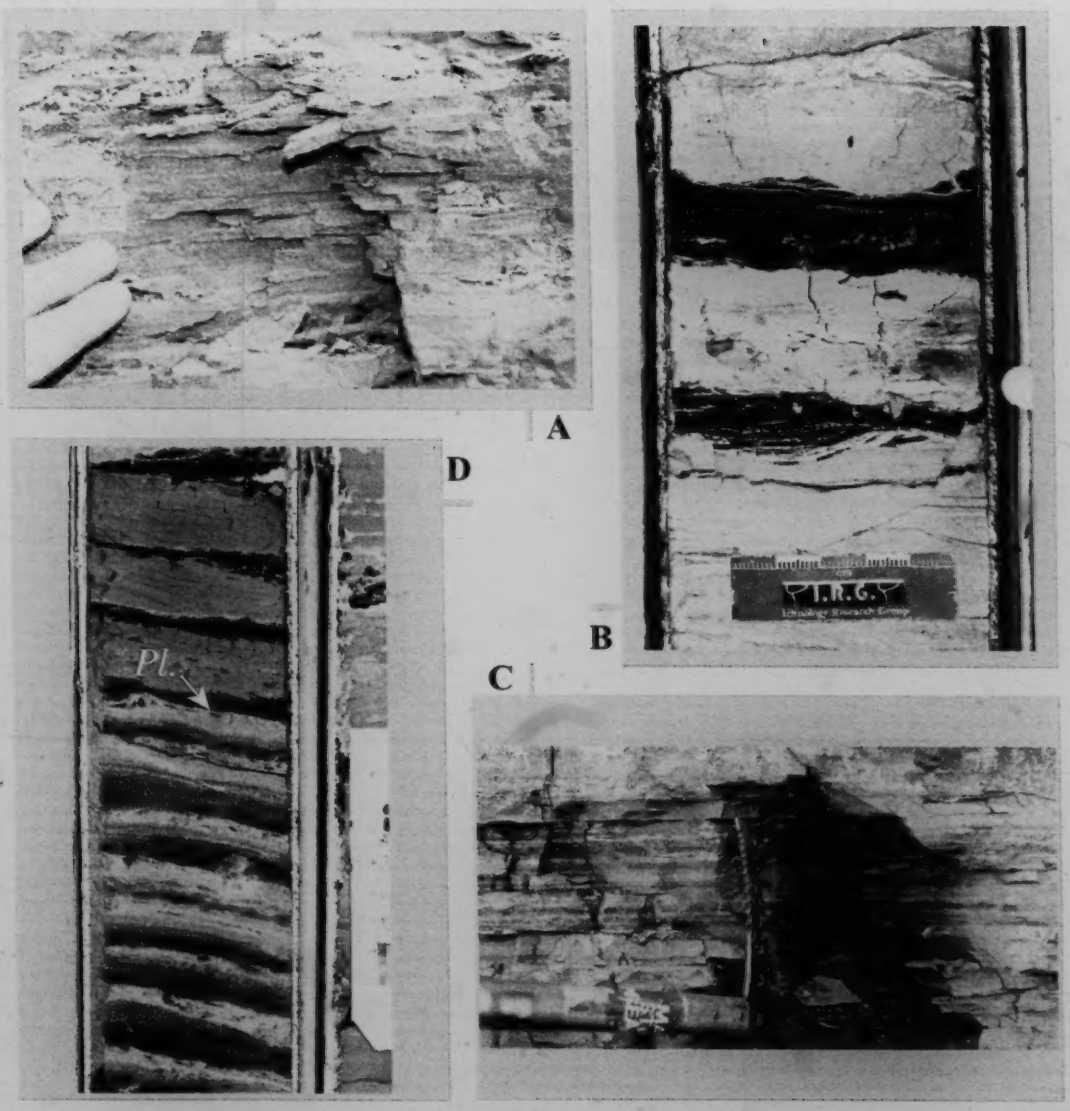


Fig. 2.13. Facies 2c. **A)** Outcrop exposure of F2c displaying the laminated nature of the mud beds as well as the shallow angle of the beds (E14). **B)** Thick mud intervals are more commonly observed in core exposures due to the lack of preserved mud-dominated facies in outcrop (14-23-95-11W4). **C)** Laminated mud-dominated IHS from outcrop E15. **D)** Increasingly muddier IHS bedding showing the gradual sand-mud change and sharp mud-sand boundary (10-20-96-11W4).

age than muds in F2b. Interlaminated muds can contain lenticular bedding. Bioturbation in this facies is absent to rare with only diminutive *Planolites* and *Arenicolites* traces found in the upper portions of this facies (Fig. 2.13d).

Facies 2c has gradational upper and lower contacts although sharp upper contacts are present in various locations. The facies typically overlies F2b sand-dominated IHS, F2e burrowed sand-dominated IHS, and is typically intercalated with burrowed mud-dominated IHS (F2f). Overlying facies include all F2 and F3 subfacies. Facies 2c may also be intercalated and overlain with the massive to laminated mudstones of Facies 4. This facies can be up to 10 meters thick.

Ichnology:

This facies is relatively barren of traces with the exception of rare *Planolites* and *Arenicolites* found in the upper portions of this facies. These traces were found to occur in low abundances in thin intervals. These traces represent the attempts of organisms to establish themselves in a dwelling and feeding behavior.

Interpretation:

Mud-dominated inclined heterolithic stratification is interpreted to represent low-energy lateral accretion deposits associated with tidally influenced point bars of a meandering fluvial to estuarine channel, similar to F2b. As with F2b, this facies is distinct due to the cyclic alternation of coarser- and finer-grained beds and laminae sets, indicating fluctuation in depositional flow conditions.

The high mud content is a distinct feature of this facies. The fine-grained nature of this facies is representative of the typically fining upward succession associated with channel point bar deposits (Jackson, 1976; Smith, 1988a). The appearance of carbonaceous debris that has settled out with the mud component of this facies indicates a quiescent environment. The majority of F2c deposits are the result of deposition within lower energy

zones of the point bar. Allen (1991) in his study of the modern Gironde estuary, a tide-dominated estuary located in France, noted a decrease in channel sediment grain size as an indicator of the fluvial to central-estuary transition. This is seen in the relationship of F2c with the sandy, more fluvially influenced facies below (F2b) and the increasingly muddier sediments experiencing increased water salinity above (F3, F4; Table 2.1).

Facies 2c can be laterally extensive and somewhat regional between core and outcrop locations. The position of this facies within a fluvial to estuarine system can explain its lateral extent. Mud deposition is a significant component of estuarine systems (Dalrymple *et al.*, 1992; Lavigne 1999; Gingras; 1999). The "turbidity maximum" is a geographic area within the estuary of high suspended fine sediment concentrations (Allen, 1991, Dalrymple *et al.*, 1992) that affects mud deposition in the central to upper estuary. Inherent to muddy IHS is the uncertainty of whether the muddy sediments are deposited as a result of deposition within the low energy environment associated with a meandering channel or whether they represent mud deposition within or due to, the turbidity maximum of the estuary.

To summarize, it is evident from the physical structures that this facies was deposited in a meandering channel environment characterized by low energy depositional conditions. Most likely, these strata accumulated in the low energy environment as laterally accreting point bars in a meandering fluvially-dominated estuarine channel.

FACIES 2D (F2D) BIOTURBATED BRECCIA IN INCLINED SAND

Description:

Facies 2d is characterized by inclined sand containing abundant bioturbated mud rip-up clasts (Fig. 2.14). This facies is more common in the lower to middle sections of the McMurray Formation in this area. This unit can range in thickness from less than one meter to five meters. The matrix of this facies is identical in all respects to the matrix of F2a. The

clasts of F2d however are quite different from F2a.

The rip-up clasts of F2d consist of mud and can range in size from 0.5cm up to 1 meter in diameter. Some clasts are so large they can appear as beds, making them easily confused with inclined bedded muds. The clasts are laminated and bioturbated, rarely appearing massive. Clasts in F2d are also generally angular to subangular and parallel the bedding planes with the long axis of their shape (Fig. 2.14d). The clasts of F2d show tidal indicators such as wavy and lenticular bedding, and double mud drapes (Fig. 2.14b). The clasts of F2d also show abundant bioturbation.

Zones of small-sized rip-ups (<2cm in diameter) occur in horizons separated from the larger clast intervals. These small clasts are typically cylindrical in shape, occasionally displaying a sand filled central shaft. These clasts occur together in thin beds of up to 15cm in thickness (Fig. 2.14a).

Facies 2d commonly has a sharp but not scoured basal contact. It typically overlies F1a, F1b, F1c, and F2e. This facies is routinely intercalated with all other sandy F2 facies. Generally this facies is gradationally overlain by F2b or F2e.

Ichnology:

The bioturbation in F2d is limited to the clasts themselves. The clasts show moderate abundances of the traces *Arenicolites*, *Planolites*, and *Cylindrichnus*. The traces are of low diversity, appearing together and in monospecific assemblages. Clasts surrounding each other show similar but not identical bioturbate fabrics (Fig. 2.14c). It is understood that these clasts were not bioturbated *in-situ*, but rather in a different nearby environment from which they were eroded and subsequently deposited in the sandy matrix.

The thin intervals of small-sized clasts appear to be ripped-up *Cylindrichnus* burrows. These clasts display the same shape and character of *in-situ Cylindrichnus* burrows with some examples appearing broken (Fig. 2.14a).

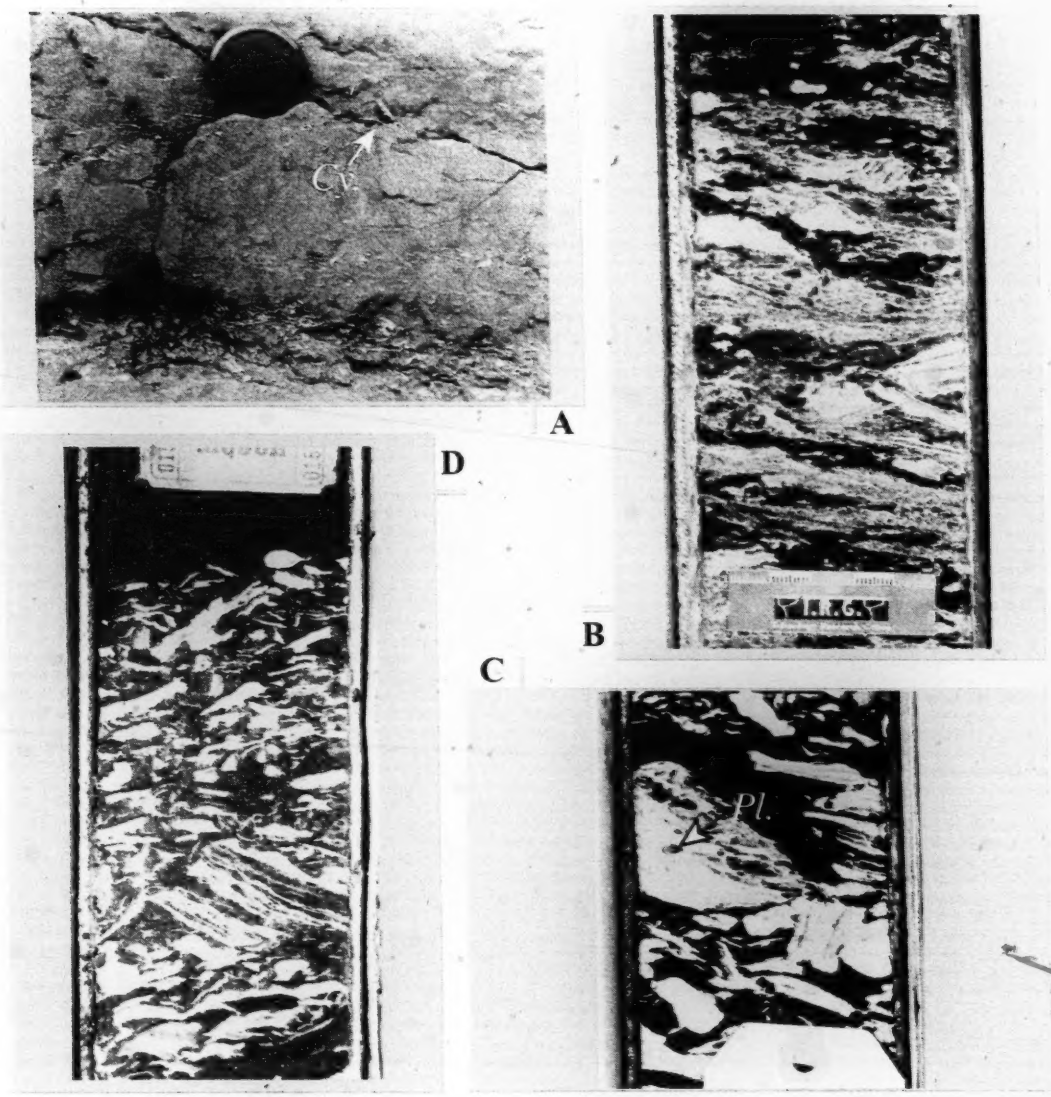


Fig. 2.14. Facies 2d. **A)** *Cylindrichnus* (Cy.) clasts at outcrop E12. Note the parallel alignment of rip-up clasts with the bedding surfaces. **B)** Poorly sorted breccia clasts paralleling the depositional angle of the bedding planes (11-3-96-11W4). **C)** Burrowed and tidally influenced clasts in core (10-3-96-11W4). **D)** Thin interval of breccia displaying a sharp base and top (7-10-96-11W4).

Interpretation:

This facies is interpreted to represent channel deposits associated with laterally accreting point bars in a meandering estuarine channel. This is similar to the environment interpreted for F2a. Facies 2d however contains larger clasts that can be attributed to bank collapse. The important interpretive difference between these two facies is the type of sediment the environment entrains for deposition. Facies 2a contains eroded and deposited unbioturbated, non-tidally influenced muds. Facies 2d contains eroded clasts of bioturbated, tidally influenced mud.

From the information held in the clasts of F2d, a picture can be created of the surrounding environmental character, or of the lateral deposits that were previously deposited. The influence of tides through tidal signatures, and brackish conditions through trace fossils can be interpreted. Strong tidal indicators and trace fossils indicate a lateral deposit of estuarine nature. This can help identify what component of the estuarine system is being eroded, and indicate what type of deposition was previously taking place at this geographic location.

The *Cylindrichnus* burrow rip-ups develop due to the erosion of sediments containing *in-situ* burrows. The fine-grained lining present in the *Cylindrichnus* burrows is well-packed and cohesive mud. This mud is capable of retaining structural integrity in moderate energy conditions and short transport distances. The *Cylindrichnus* rip-ups were most likely sourced from erosion of the outer bank sediments in a meandering estuarine channel environment. The presence of these rip-up clasts indicate erosion of sediments that were deposited under brackish conditions such as the estuarine deposits of F2e sand dominated, burrowed, IHS.

To summarize F2d, the physical structures and breccia clasts suggest that this facies was deposited in a meandering channel environment characterized by pulses of high-energy conditions. Most likely, these strata accumulated as deeper channel equivalents of laterally accreting point bars in a meandering estuarine channel.

FACIES 2E (F2E) SAND-DOMINATED BURROWED INCLINED HETEROLITHIC STRATIFICATION

Description:

Facies 2e is characterized by inclined, thickly interbedded and finely interlaminated sand and mud with bioturbation (Fig. 2.15). This facies is most common in the middle section of the McMurray Formation. This facies is identical to F2b with respect to physical structures and lithologic accessories. Only the components of F2e that differ from F2b will be discussed here. Rip-up clasts are more similar to those in F2d rather than those of F2a. Bioturbation of the sandy and muddy layers is common in F2e.

Facies 2e has gradational upper and lower contacts, except when scoured into by F1a, F2a, F2b, and F2d. This facies commonly overlies F1 and F2 sediments (Table 2.1). This facies is intercalated with all F2 facies. Facies 2e can be overlain by F2c, F2f, F3a, and F3b. This unit can be up to 20 meters thick.

Ichnology:

Bioturbation intensity and abundance within F2e may range from locally absent to abundant, with some low-diversity, intensely burrowed horizons. Burrows are limited to the fine-grained mud layer or extend from this mud layer into the sand layer. Trace fossils present include: *Cylindrichnus*, *Planolites*, *Gyrolithes*, *Arenicolites*, *Skolithos* and fugichnia (escape traces)(Fig. 2.15d). Fugichnia are only found in the sand layer.

Low-diversity to monospecific assemblages are a defining feature of sand-dominated, bioturbated IHS (Fig. 2.15a). The aforementioned trace fossils are never found to colonize the same bedding plane, and are rarely observed together in the IHS bedded couplets. *Planolites* and *Arenicolites* are recognized in this facies by the sand-filled, sharp-walled circular burrows crossing the mud from a start-point in a sandy layer. The number

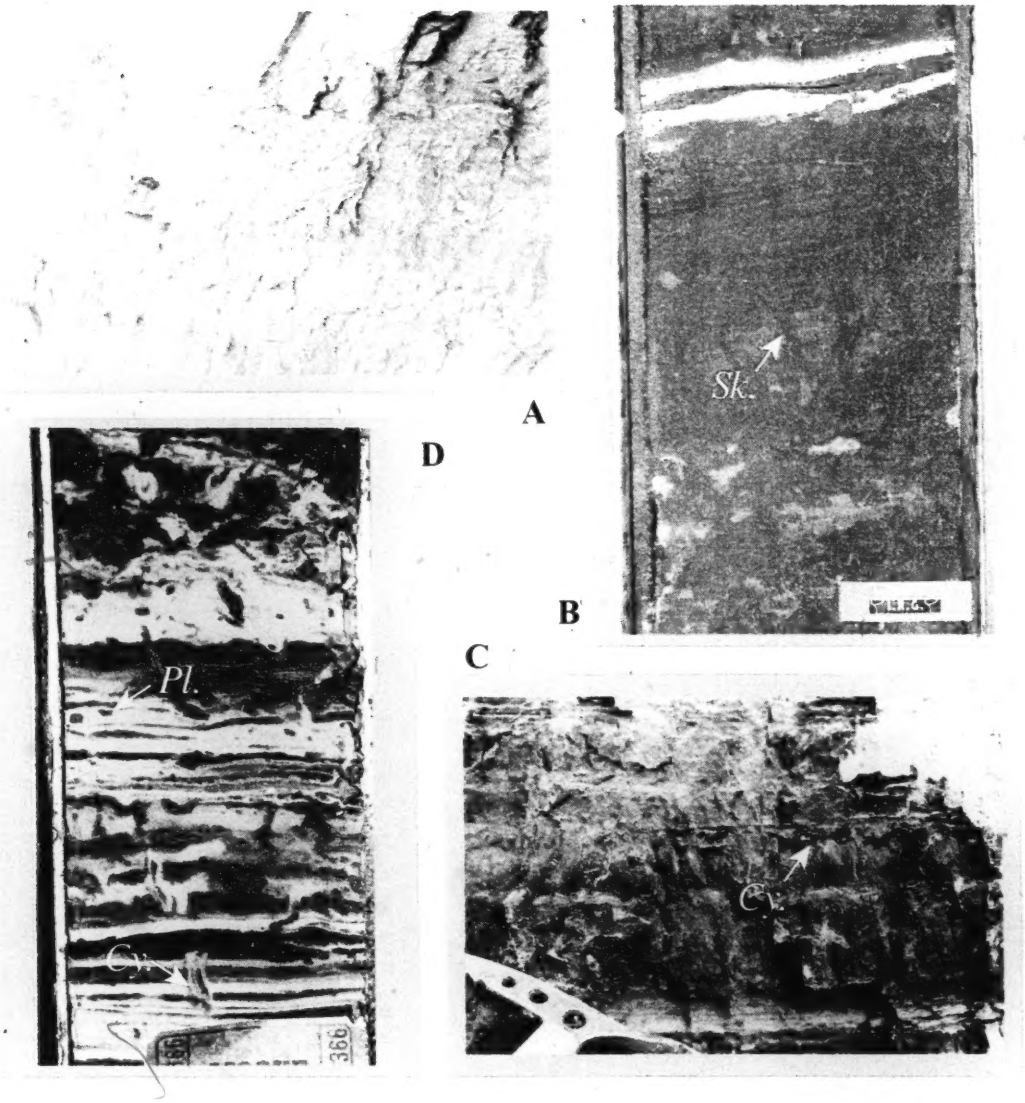


Fig. 2.15. Facies 2e. **A)** Outcrop examples of bioturbated IHS sediments containing *Cylindrichnus* (Cy.) burrows. **B)** Sandy interval with thin mud couplets above. Note the vertical *Skolithos* (Sk.) burrows (15-9-96-11W4). **C)** Outcrop example of sand-dominated, vertically burrowed IHS. **D)** Core example of bioturbated muds in sand-dominated IHS *Planolites* (Pl.) and *Cylindrichnus* (Cy.) are common (12-26-95-11W4).

of burrows decrease away from the sand-mud interface. *Planolites* is a common element of the McMurray Formation in the study area as the organism responsible for making this trace is hardy and can exist in a wide variety of environmental conditions.

The vertical trace fossils *Cylindrichnus*, *Arenicolites*, *Skolithos*, and *Gyrolithes* have been observed to possess a preferred burrow orientation (Beynon and Pemberton, 1992; Bechtel, 1996). In these cases, the long axis of the burrow is perpendicular to the IHS bedding planes. In this study, *Skolithos*, *Arenicolites* and *Cylindrichnus* are not generally oriented perpendicular to bedding. Two types of *Gyrolithes* have been noted from this study area, and have been classified using their spiral to length ratio (Bechtel, 1996). The *Gyrolithes* Type I has a higher radius spiral to length ratio with a greater shaft diameter, giving it a more robust appearance, and appearing in the sand component of the sand-dominated IHS and horizontally interbedded facies. Type II *Gyrolithes* has a longer length to radius spiral diameter and is commonly found in mud-dominated bioturbated IHS (F2c, F2f), and also in the massive to laminated muds of F4a (Fig. 2.16).

Interpretation:

The trace fossil assemblage of F2e represents brackish conditions in the depositional environment. Brackish trace fossil assemblages have distinctive characteristics (Pemberton *et al.*, 1982; Wightman *et al.*, 1987; Beynon and Pemberton, 1992; Pemberton and Wightman, 1992; 1995; Pemberton *et al.*, 1992; Ranger and Pemberton, 1992; Lavigne, 1999; Gingras *et al.*, 1999a; 1999b; Harris *et al.*, 2001). These include: 1) trace fossils that are typically smaller than their fully marine counterparts due to stressed conditions; 2) morphologically simple forms; 3) low diversity, including locally monospecific assemblages; 4) high abundances; and 5) a combination of traces from both the *Skolithos* and *Cruziana* ichnofacies due to fluctuating energy conditions producing substrates of variable consistency. Trace fossils found in F2e that are attributed to brackish conditions include: *Skolithos*, *Planolites*, *Arenicolites*, *Teichichnus*, and *Gyrolithes*. The only other unmen-

tioned trace, fugichnia, an escape trace, is associated with episodic deposition reflecting fluctuating energy conditions.

The ichnofossil assemblage represents not only a response to salinity stress, but also to the variable depositional conditions. Monospecific assemblages of *Cylindrichnus*, *Arenicolites*, and *Gyrolithes* reflect opportunistic colonization of the substrate following stressed environmental conditions. Stresses to a marine organism population are the result of several factors, including: turbidite deposition, oxygen deficiencies, storm deposition, or salinity variations (Pemberton *et al.*, 1992). It is possible in this case that the stress event prior to colonization was not a storm event, and much more likely to be a high-energy depositional event associated with tidal or estuarine flooding. Strong physico-chemical stresses such as salinity variations and alternating current strength account for the lack of a fair-weather equilibrium population in F2e. The cyclic nature of these events results in the repetition of monospecific assemblages observed in this environment.

Type I *Gyrolithes* is a common trace fossil in this facies. Although it is present in other facies, the monospecific character and burrow morphology of this trace are indicative of marginal marine environments (Gernant, 1972). The monospecific *Planolites* assemblage found within this facies is also evidence of the cyclic nature of this depositional environment (Bechtel *et al.*, 1994). These unlined open burrows could not be sustained within soft mud, yet they occur in the mud or 'fine' layers of the IHS couplet. The sharp-walled nature of these *Planolites* and structureless sand fill indicate colonization of the mud while it was in a cohesive state and passive infill of the burrow from the overlying sand layer on deposition (Bechtel, 1996). These features are consistent with the *Glossifungites* ichnofacies (Pemberton and Frey, 1985; MacEachern *et al.*, 1992, Gingras *et al.*, 2000) where a depositional hiatus accompanied by subsequent erosion provided a firmground substrate into which burrows could penetrate. This study does not attempt to assign the stratigraphic significance commonly associated with the *Glossifungites* surface (MacEachern *et al.*, 1992; Gingras *et al.*, 2000), but rather a short autocyclic feature due to depositional hiatus

in a dynamic environment.

The change in water level associated with tidal fluctuations dewaters and compacts the muds during low water levels. The high water levels submerge the sediment, allowing colonization of the surface by opportunistic organisms. Sand is subsequently deposited which then passively infills the open burrows created by the organisms in a subaqueous environment.

Thomas *et al.*, (1987) suggested the presence of trace fossils as significant criteria for distinguishing and separating estuarine from fluvial inclined interbeds. An interesting feature to the bioturbation is that burrows only occur on the surfaces separating sand and mud interbeds. There is no bioturbation related to the incongruent appearing surfaces defined by the internal interlaminae. It is inferred that the interlaminae most likely represent daily tidal signatures generated by slightly higher and lower flow velocities. The lack of bioturbation on these couplets reflects the inability of organisms to actively burrow during the short-lived slack water periods as inferred by Pollard *et al.* (1993). The bioturbation found on the bedded couplets is interpreted as deposition related to seasonal changes in flow conditions in the estuarine channels. The muddy components of the IHS beds have been interpreted to be deposited during slack water periods resulting from lower current energies related to tidal reversals (Thomas *et al.*, 1987; Smith, 1988a). This is a relatively short time for organisms to colonize a substrate prior to organism evacuation and subsequent infill by the overlying sand layer. The hiatus associated with these horizons has been termed the "colonization window" by Pollard *et al.* (1993). This is a fundamental concept when analyzing ancient deposits for the importance and degree of tidal influence (Lavigne, 1999). Every alternation from sand to mud to sand should allow for colonization by organisms due to the decrease in current energy required to deposit the finer-grained sediment, but burrowing is not present in every lamination. The coarse and fine beds of the IHS deposits in the McMurray Formation are hereby interpreted to be a seasonal phenomenon based on the low energy levels and time required for certain ichnofossils (i.e. *Cylindrich-*

nus, *Gyrolithes*, *Arenicolites*) to colonize the fine substrate. De Mowbray (1983) noted seasonal changes in the mudflats of Scotland result in bioturbated and unbioturbated intervals. Sand deposition is interpreted as a winter feature due to increased precipitation and fluvial discharge and the displacement of the salt wedge seaward. Mud deposition and increased bioturbation is interpreted as a summer phenomenon due to lower fluvial discharge levels allowing the salt wedge to encroach landward with it's accompanying bioturbation and increased mud-deposition due to the turbidity maximum (de Mowbray, 1983). The reactivation surfaces may be exposed longer due to seasonal conditions and exhibit more extensive bioturbation (Allen, 1980; Lavigne, 1999). Examples of seasonal colonization on reactivation surfaces are evident in figure 2.7a from subfacies F1b, as well as the burrowed inclined interbedded sediments of F2 (Fig. 2.15a).

To summarize, the physical and biogenic structures suggest that this facies was deposited in an environment characterized by exceptionally dynamic depositional conditions with brackish water conditions and strong tidal influences associated with the central estuary. Most likely, these strata accumulated as laterally accreting point bars in a meandering fully-estuarine channel.

FACIES 2F (F2F) MUD-DOMINATED BURROWED INCLINED HETEROLITHIC STRATIFICATION

Description:

Facies 2f is characterized by inclined, thickly interbedded and finely interlaminated mud and sand with bioturbation (Fig. 2.16). This facies is most common in the middle section of the McMurray Formation. This facies is identical to F2c with respect to physical structures and lithologic accessories, therefore only the components of F2f that differ from F2c will be discussed here. Synaeresis cracks are more common in F2f, and bioturbation is common throughout.

Facies 2f has gradational upper and lower contacts although sharp upper contacts are present in various locations. The facies typically overlies F2e sand-dominated burrowed IHS, F2b unburrowed sand-dominated IHS, and is typically intercalated with unburrowed mud-dominated IHS (F2c). Overlying facies include all F2 and F3 sediments (Table 2.1). Facies 2f is also often intercalated and overlain with the massive to laminated mudstones of Facies 4. This facies can be up to 10 meters thick.

Ichnology:

Bioturbation intensity and abundance within F2f may range from locally absent to common, with some low-diversity horizons abundant with bioturbation. Burrows are commonly limited to the fine-grained mud layer or extend from this mud layer into the underlying sand bed. Completely unburrowed beds of mud can be locally intercalated with highly bioturbated beds. Trace fossils observed include: *Cylindrichnus*, *Planolites*, *Gyrolithes* (Type I and II), *Teichichnus*, and rare *Arenicolites* (Fig. 2.16).

Low-diversity horizons and monospecific trace fossil assemblages are a characteristic feature of the mud-dominated, bioturbated IHS facies (Fig. 2.16). The monospecific assemblages consist either of *Cylindrichnus* or *Gyrolithes* (Fig. 2.16a). Low-diversity assemblages involving the aforementioned traces also occur in F2f. The number of burrows decrease away from the sand-mud interface at each major couplet.

Interpretation:

Mud-Dominated Burrowed Inclined Heterolithic Stratification (F2f) is interpreted to represent low-energy lateral accretion deposits associated with tidally influenced point bars in a meandering estuarine channel, similar to F2c. As with F2c, this facies is distinct due to the mud and sand ratio and the cyclic alternation of coarser- and finer-grained beds, indicating fluctuation in depositional flow conditions. The section pertaining to F2b has extended discussions on the interpretation of the tidal and estuarine influence on these deposits. As

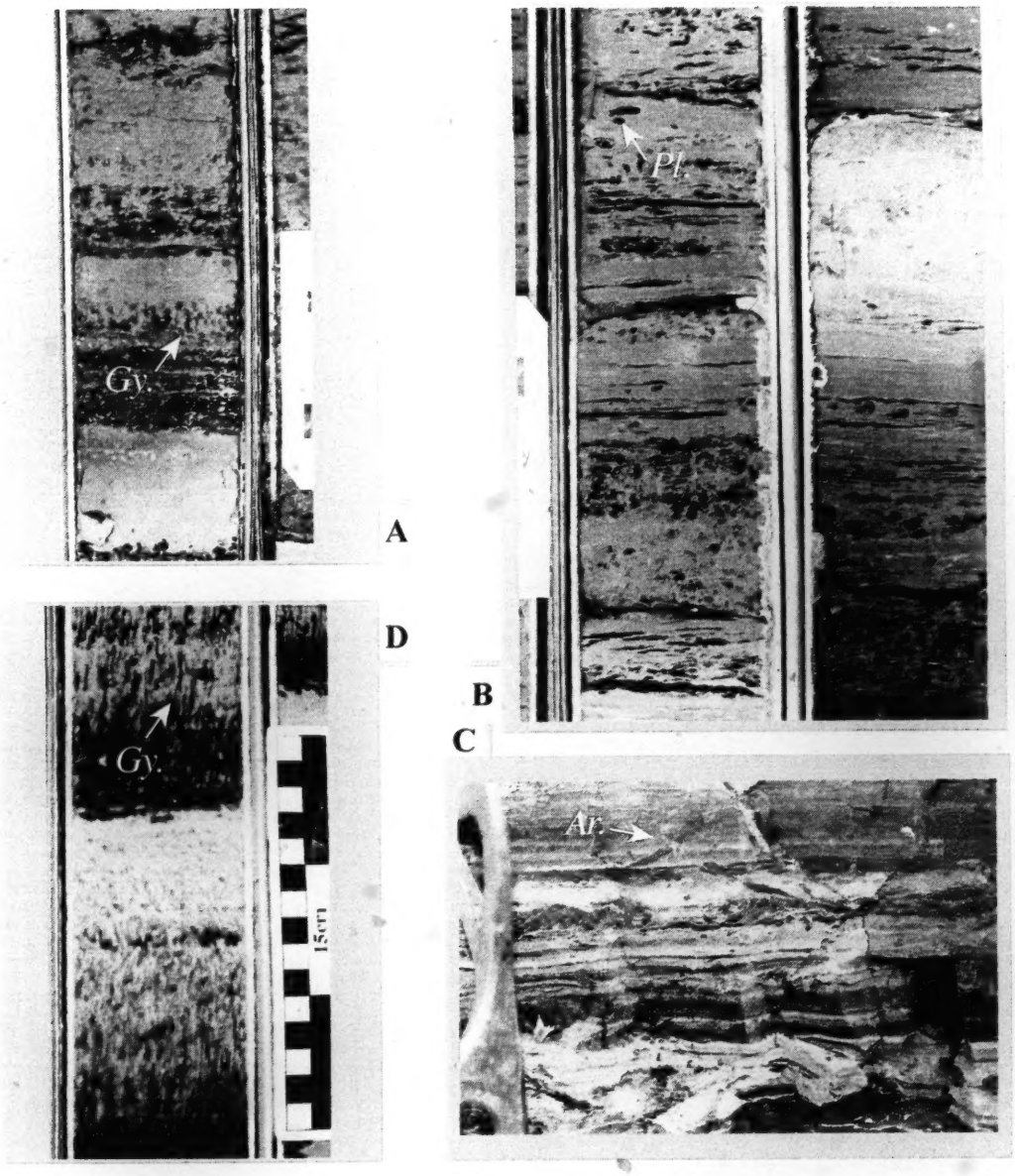


Fig. 2.16. Facies 2f. **A)** Type 1 *Gyrolithes* subtending from burrowed mud beds into the underlying sand (10-20-96-11W4). **B)** Muddy IHS sediments with abundant bioturbation from core 7-10-96-11W4. **C)** Outcrop E15 displays the nature of the sand-mud contacts. **D)** Monospecific Type II *Gyrolithes* (Gy.) subtending from thick mud beds (15-9-96-11W4).

such, the discussion here will be limited to those features distinct to F2f. The most significant of these is the brackish signature displayed within F2f. This is suggested by an increased presence of synaeresis cracks and the development of a bioturbated sediment fabric.

The trace fossil assemblage of F2f demonstrates the brackish conditions for reasons outlined in F2e. The abundantly burrowed sections in this facies are consistent with the findings of Dorjes and Howard (1975) who noted that the 'upper middle' section of the Ogeechee River/Ossabaw Sound estuary was completely mottled by biogenic processes, with only rare beds containing visible sedimentary structures. This pattern of bioturbation was also observed by Gingras (1999) within the Willapa Bay estuary in Washington.

The appearance of the Type II *Gyrolithes* may represent a response to a more ecologically harsh depositional environment (Bechtel, 1996). The smaller size of Type II *Gyrolithes* reflects the higher physico-chemical stresses associated with salinity variations and turbidity factors in the central part of the estuary. Beynon and Pemberton (1992) interpreted the behavior of *Gyrolithes* to reflect the organism's attempt to escape salinity fluctuations. The lack of tapering and increased depth of penetration relative to shaft diameter of *Gyrolithes* Type II may reflect the trace-makers enhanced escape capabilities relative to *Gyrolithes* Type I (Bechtel, 1996).

As with F2c, there is an integral uncertainty to muddy IHS as to whether the muddy sediments are deposited as a result of deposition within the low energy environment associated with a meandering channel or whether they represent mud deposition within or due to, the turbidity maximum of the estuary. The increased salinity inferred by the presence of a limited but prominent trace fossil suite suggests that the muddy IHS of F2f were deposited well within the seasonal limit of the salt wedge and the aforementioned turbidity maximum.

To summarize, it is evident from the physical structures that this facies was deposited in a meandering channel environment characterized by low-energy yet dynamic depo-

sitional conditions of brackish salinity.

FACIES 3 (F3) HORIZONTALLY BEDDED INTERBEDDED SANDS AND MUDS

Several subfacies found in sediments of the McMurray Fm. are found to be horizontally bedded with primary interbeds of sand and mud. The subfacies mainly occur throughout the middle and upper sections of the McMurray Fm. The association is made up of five facies: sand-dominated, horizontally bedded interbedded sand and mud (F3a), horizontally bedded, equally interbedded sand and mud (F3b), mud-dominated, horizontally bedded interbedded mud and sand (F3c), horizontally interbedded sand and mud with robust bioturbation (F3d), and pervasively churned sand and mud with robust bioturbation (F3e).

These facies are commonly intercalated together in many core and outcrop examples. The subfacies of F3 intercalate between F3a, F3b, and F3c, and between F3d and F3e.

FACIES 3A (F3A) SAND-DOMINATED HORIZONTALLY INTERBEDDED SAND AND MUD

Description:

Facies 3a is characterized by sand-dominated horizontally bedded, interbedded and finely interlaminated sand and mud (Fig. 2.17). This facies is more common in the middle sections of the McMurray Formation in this area. This facies is somewhat unique in that it is laterally continuous and can be correlated across wells and outcrop exposures. Facies 3a is characterized by thin interbeds of sand and mud with varying degrees of burrowing. This facies is one terminus of a continuum that has mud-dominated horizontally bedded interbedded sand and mud (F3c) as its counterpart. The rhythmic bedding can vary in thick-

ness from 0.5 cm to 6 cm with rare sand beds reaching a thickness of 25cm. Thin sand interbeds are identified to contain low-angle, planar laminations (1mm thick). The thicker individual sand beds are seen to be current ripple laminated and horizontal to low-angle planar laminated (Fig. 2.17a). There are combined flow ripples in the thick sand beds. Thick successions with this physical character composed of sand are represented by F1c. Mud interbeds generally appear structureless with an element of lenticular to wavy bedding when associated with thin sand laminae (Fig. 2.17b). The light grey mud of F3a appears similar to the mud described in Facies 4a. Double mud drapes are also a feature of F3a. Contacts undisturbed by bioturbation are typically sharp to slightly gradational.

Grain size in this facies ranges from lower very fine to upper very fine sand. Most sand grains are rounded to sub-rounded. The horizontal character of the sand beds and mud laminae distinguish this facies from F2 sand-dominated facies. Individual sand laminae in F3a can vary from 1mm to 5mm in thickness. The laminations are sharp based and grade upwards into fine silt, mud, and carbonaceous detritus. The carbonaceous debris in F3a are upper fine-grained sand grain size and typically aid in defining bedding as they drape many bedforms. The laminae do appear to have a cyclic or rhythmic pattern that appears as tidal bundles and double mud drapes when not obscured by biogenic structures (Fig. 2.17).

The sand beds of this facies typically accumulate more sediment than the mud counterparts. Examples of 30 centimeter burrowed sands with very thin mud laminae have been identified from core. These sharp-based and sharp-topped sands routinely contain current ripple, combined flow ripple, and climbing cross-laminated beds intercalated with horizontal to low-angle planar stratified sand. The grains are typically surrounded and well sorted. Coal or wood fragments as well as synaeresis cracks are common features of F3a. Rooting is very common within the mud beds. Bioturbation is also common in this facies.

Facies 3a has gradational upper and lower contacts although sharp contacts are present in various locations. The facies typically overlies F1c and the F2b, F2c, F2e, and F2f IHS bedded facies. Commonly F1c, F3a, F3b, and F3c are intercalated. F3a also inter-

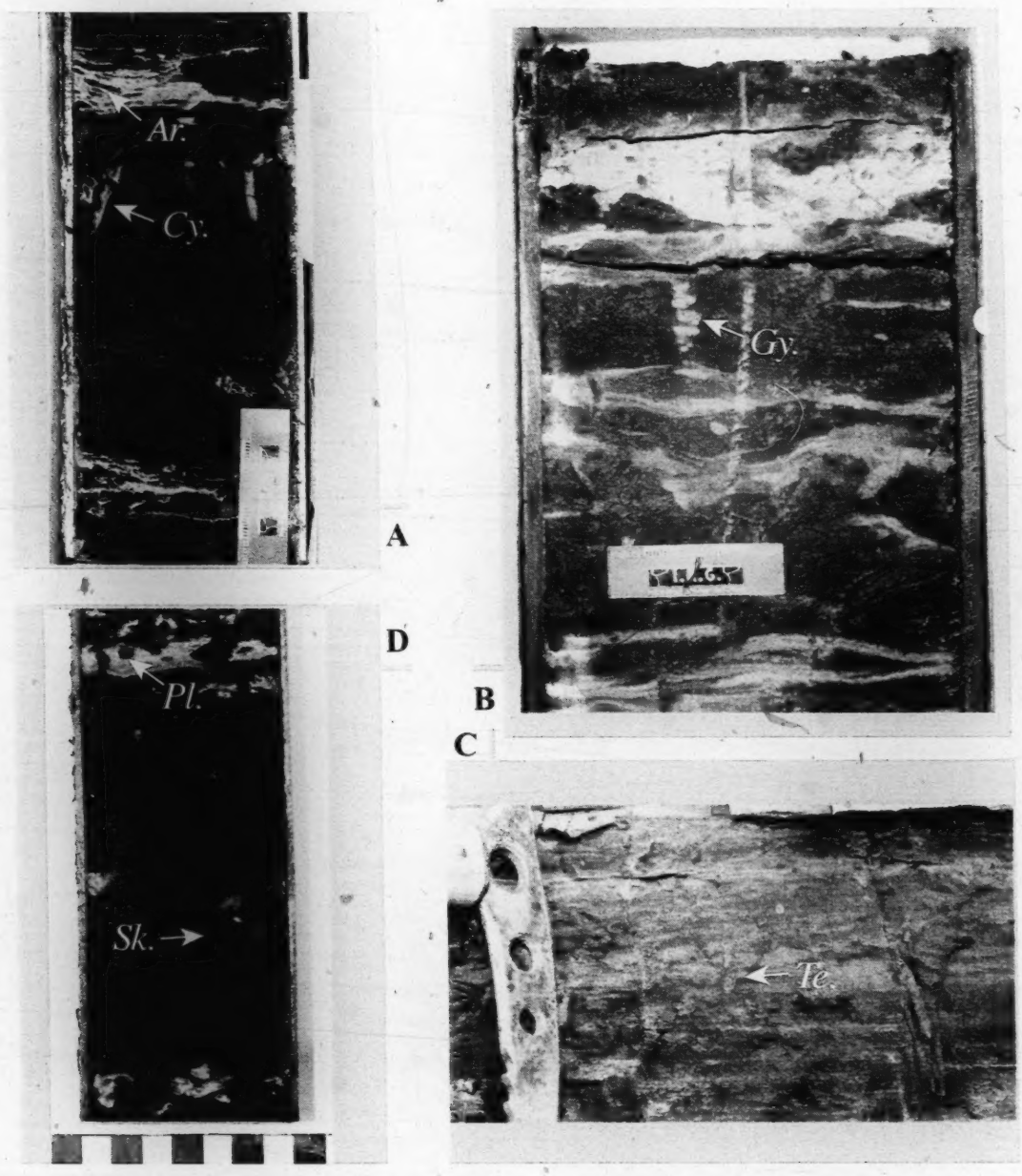


Fig. 2.17. Facies 3a. **A)** *Cylindrichnus* (Cy.) and *Arenicolites* (Ar.) in core (13-33-95-11W4). **B)** *Gyrolithes* (Gy.) developed in a moderately bioturbated sediment (11-3-96-11W4). **C)** Outcrop E15 displays an estensive sandy flat component including rare *Teichichnus* (Te.). **D)** *Planolites* (Pl.) is best identified in the mud component while the vertical trace *Skolithos* (Sk.) is best seen in moderately saturated sand (5-23-95-

calates with the F2 subfacies. It has been observed in outcrop to overly F4a muds. This unit can reach a thickness of 4 meters.

Ichnology:

Bioturbation intensity in F3a can range from rare to common. Trace fossil abundances in F3a are considered moderate. The trace fossil assemblage is similar to the assemblage of F2e. The trace fossils identified include: *Planolites*, *Cylindrichnus*, *Skolithos*, *Arenicolites*, rare *Gyrolithes* and *Teichichnus* (Fig. 2.17). In outcrop, fugichnia (escape traces) have been identified in the thicker sands that otherwise have limited bioturbation. As the majority of these traces have been discussed previously, the discussion will be limited to the commonly occurring *Teichichnus* of F3a. *Teichichnus* is an unbranching, horizontal feeding behavior that migrates up or down in the sediment column leaving distinctive laminae representative of the position of a previous burrow wall (spreiten). This trace is indicative of the behavior of an organism as it attempts to deepen its burrow, separating itself from the sediment-water interface. These burrows are most common in the sand bed layers.

Overall trace fossil size is small while the population in general is of low diversity. Facies 3a does not contain the monospecific assemblages noted from F2e and F2f but can develop low diversity horizons.

Interpretation:

Facies 3a is interpreted to represent deposition within sand-dominated tidal flats. Due to the intercalating and gradational association of F3a with the deposits of F2c and F2e, it is interpreted that these tidal flat deposits flanked an estuarine channel and point bar complex rather than occurring as widespread coastline tidal flats such as those described by Evans (1965) or Klein (1977). In modern examples, the environment of tidal flat deposition is stratigraphically higher than that for depositing a point bar complex and as such,

represents the vertical aggradation component of an estuarine meandering channel succession. Fringing tidal flats have been described from the Gironde estuary (Allen, 1991) and from the Willapa Bay estuary (Clifton, 1983; Gingras, 1999).

The combination of horizontal to low-angle planar stratification and current ripple to combined flow rippled sand demonstrates the fluctuating character of this depositional regime. Harmes and Fahnestock (1965) noted that horizontal planar stratification is the result of upper flow regime plane beds. Upper flow regime planar beds form under high energy in shallow waters. Grain size also influences this type of bedding as planar stratified deposits form under lower energies for fine-grained sand than they do for coarse-grained sand. Deposition of ripple beds occurs under lower flow regime conditions. The decrease in flow regime indicates the gradual lowering of flow velocity most likely associated with flood conditions or tidal slack-water conditions. The sand flat is an area dominated by flood conditions versus ebb conditions (van Straaten, 1964). Grain sorting and grain shape are important factors in intertidal sedimentation. Irregular particles with sharp edges are more likely to be plucked by tidal currents and carried away due the rollability of the rounded grains (Winkelmolen and Veenstra, 1974). As such, sand in this environment is composed of rounded to subrounded grains.

The interlaminated sand and mud in this facies reveal an overall tidal character due to the double mud drapes and wavy to lenticular bedding (Reineck and Wunderlich, 1968). Wavy and lenticular bedding are not terms used exclusively for tidal deposits, although they are a commonly used as indicators of such environments (Reineck, 1967; Reineck and Wunderlich, 1968; Klein, 1977; Nio and Yang, 1991; Eisma, 1998). Wavy and lenticular bedding are the result of cyclic energy conditions with sand representing the higher flow conditions and mud representing the lower flow conditions. Under tidal conditions the sand is deposited with bedload traction during current flows while the mud is attributed to suspension deposition during slack-water conditions (Reineck and Singh, 1980; Eisma, 1998). Dalrymple *et al.* (1991) noted that in modern tidal flat systems in Cobequid Bay, bed thick-

ness varies laterally whether mud or sand dominated. Rhythmites from unburrowed tidal flat facies in core 14-23-95-11W4 show neap-spring cycles of increased sand and/or mud deposition (Fig. 2.18a).

The trace fossil assemblage of F3a indicates a higher diversity than any facies encountered thus far in the estuarine environment. One of the reasons for this may be the increased marine influence and the position of tidal flats relative to estuarine channels. Studies of the Ogeechee River/Ossabaw Sound estuary (Dorjes and Howard, 1975; Howard *et al.*, 1975) and Willapa Bay Estuary (Gingras, 1999) describe an increase in species diversity towards the fully marine environment. The trace fossils of F3a are smaller when compared to their marine counterparts. This is similar to trace fossils found in F2 facies. The diminutive marine trace fossil assemblage is indicative of brackish water conditions in an otherwise hospitable environment (Pemberton *et al.*, 1982; Pemberton and Wightman, 1992; Wightman and Pemberton, 1997). The synaeresis cracks present in the muds suggest fluctuating salinities common on the tidal flat (Plummer and Gostin, 1981). The rooting suggests shallow depths.

To summarize, it is evident from the physical and biogenic structures that F3a was deposited in a sand-dominated tidal flat environment characterized by exceptionally dynamic depositional conditions in a brackish environment. The location of deposition was also flanking the laterally incising estuarine channels.

FACIES 3B (F3B) HORIZONTALLY BEDDED EQUALLY INTERBEDDED SAND AND MUD

Description:

Facies 3b is characterized by horizontally bedded, interbedded and finely interlaminated sand and mud (Fig. 2.19). This facies is common in the middle sections of

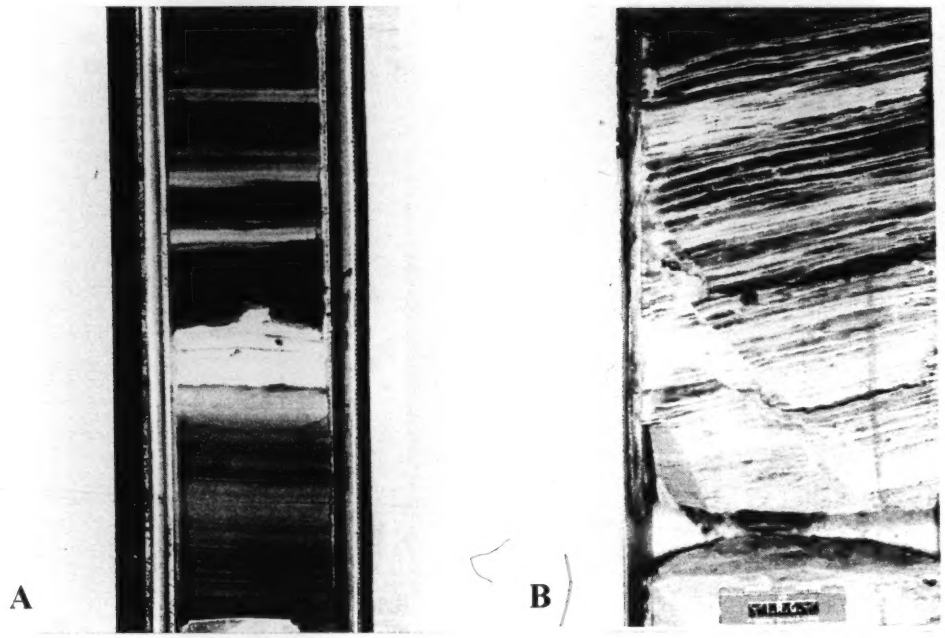


Fig. 2.18. Tidal Indicators. **A)** Tidal couplets from facies 3a (F3a) in core 14-23-95-11W4. **B)** inclined tidal structures from facies 2f (F2f) in core 11-3-96-11W4.

the McMurray Formation in this area. This facies is centrally positioned in a continuum that has sand-dominated horizontally bedded interbedded sand and mud (F3a) and mud-dominated horizontally bedded interbedded sand and mud (F3c) as terminal members. The rhythmic bedding character can slightly vary in bed thickness from 0.5cm to 3cm. Laminations are consistently 1mm to 0.5cm thick. Pervasive bioturbation generally obliterates contacts between individual sand and mud beds, precluding the identification of the physical structures of the individual beds. The internal character of the sand and mud beds where visible is similar to the character of the thin sands and muds of F3a and as such will not be discussed here. This facies also contains abundant rooting and disseminated carbonaceous debris. The sand and mud beds are consistent in grain size and sorting with F3a, F3b, and F3c. The only differences arise in ratio concentrations of sand and mud, and the internal

bedding of the thick sands (F3a) and thick muds (F3c). Pervasive bioturbation is a defining feature of F3b (Fig. 2.19b). Contacts undisturbed by bioturbation in F3b are rare and sharp to slightly gradational.

Facies 3b commonly has gradational upper and lower contacts with rare abrupt upper contacts related to F3a. This facies is typically intercalated with F1c, F3a and F3c and can be intercalated with the F2 facies.

Ichnology:

A defining feature of F3b is the pervasive bioturbation that typically obliterates primary sedimentary structures. The trace fossil assemblage is identical to that of F3a and as such will not be discussed at length. Facies 3b contains such identifiable trace fossils as: *Planolites*, *Cylindrichnus*, *Skolithos*, *Arenicolites*, rare *Gyrolithes*, and *Teichichnus* (Fig. 2.19). The trace fossil intensity in F3b can range from rare to pervasive with most examples from core and outcrop displaying pervasively bioturbated sediment (Fig. 2.19a). Tracemakers in the environment of F3b consistently crosscut each other's burrows, making distinction of the individual traces more difficult than if they were less pervasive.

Monospecific assemblages are not common in this facies as trace fossils in F3b are often found in horizons burrowed by many, if not all, identified trace fossil genera. This is slightly different than F3a where low-diversity horizons can be commonplace.

Interpretation:

As with F3a, F3b is interpreted as being deposited in a tidal flat environment. Due to the equal ratio of sand and mud components in this facies, it is interpreted that F3b represents a 'mixed' flat environment. The gradational relationship of this deposit with the estuarine channel deposits of F2e and F2f, and the intercalation with F3a, further suggests that F3b was a tidal flat deposit. The depositional mechanisms of tidal flats in general have

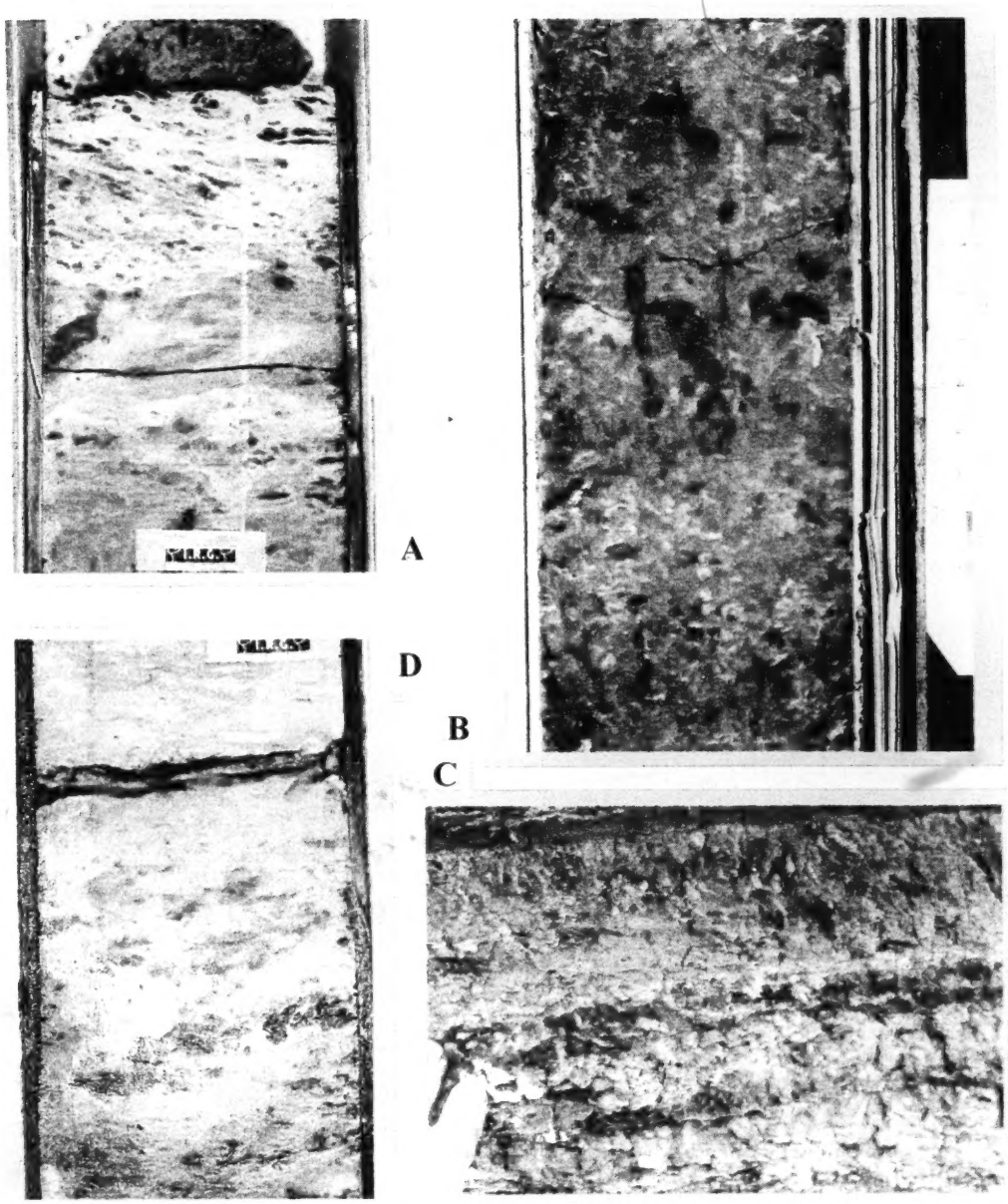


Fig. 2.19. Facies 3b. **A)** Pervasively churned sediment from F3b (11-3-96-11W4). **B)** No vestigial laminations are preserved in this example of equal mud and sand (9-9-96-11W4). **C)** Disseminated mud mixed with sand by biogenic processes (14-23-95-11W4). **D)** Outcrop E14 displays a two meter thick interval of heavily churned sediment.

been discussed in the interpretation of F3a and as such will not be discussed here. This discussion will focus more on the defining characters of F3b.

Equal sand and mud deposition indicates that there were not the episodic flooding events that characterized the deposition of F3a. The sediment of F3b was deposited under rhythmic conditions such as tidal currents with an equal bias towards sand and mud. The bioturbation also indicates an environment of low to moderate energy and sufficient salinity due to the abundant reworking of the sediment by organisms. The mix of sand and mud was appropriate for the organisms to colonize. Gingras *et al.* (1999a) note from deposits at Willapa Bay that strongly burrowed fabrics are the result of low sedimentation rates and high rates of reworking on the intertidal flats. The low sedimentation rates of this facies are shown in the thin bedded, equal proportions of sand and mud in the rarely bioturbated localities. The increased bioturbation is the result of increased salinity and decreased physical reworking in the environment. De Mowbray (1983) and Gingras *et al.* (1999a) propose that episodic paucity of burrowing could be related to seasonal changes in the bay environment. This is similar to seasonal changes in bioturbation seen in the bioturbated IHS facies F2e and F2f.

Gingras *et al.* (1999a) reported modern tidal flat deposits from Willapa Bay, Washington that contained thoroughly churned sediments from bioturbation similar in appearance to F3b. Radiograph images of adjacent Pleistocene intertidal deposits bordering Willapa Bay show such abundant biogenic reworking that only subtle overall grain size changes represent the vestigial laminations.

To summarize F3b, it is evident from the biogenic structures that this facies was deposited in an centrally located, equally mixed, sand and mud tidal flat environment characterized by dynamic depositional conditions in a brackish salinity environment. Deposition of this facies occurred somewhat distal to the active estuarine channel area as conditions needed to be moderate to deposit both sand and mud.

FACIES 3C (F3C) MUD-DOMINATED HORIZONTALLY BEDDED INTERBEDDED SAND AND MUD

Description:

Facies 3c is characterized by mud-dominated horizontally bedded, interbedded and finely interlaminated mud and sand (Fig. 2.20). This facies is common in the middle sections of the McMurray Formation in this area. Facies 3c is characterized by regular interbeds of mud and thin sand with varying degrees of burrowing. This facies is part of a continuum that has sand-dominated, horizontally bedded interbedded sand and mud (F3a) as its counterpart. Facies 3c contains similar physical structures and lithologic accessories to F3a. The key difference between these two facies is that F3c has a greater than 50% mud content. The mud beds of F3c range in thickness from 0.5cm to 15cm with rare mud beds reaching a thickness of 25cm. The sand interbeds are thinner with a maximum bed thickness observed at 15cm. Mud beds of F3c are massive to finely laminated with abundant lenticular and wavy style bedding. Interlaminae within the mud and sand beds can be 1 mm to 0.5 cm in thickness. The light grey mud of F3c shares features with the mud described in Facies 4a. Double mud drapes are also a feature of F3c. Synaeresis cracks are abundant in the muds of this facies. Contacts undisturbed by bioturbation are typically sharp to slightly gradational.

Facies 3c commonly has gradational upper and lower contacts with rare abrupt upper contacts related to F1c and F3a. This facies is typically intercalated with F1c, F3a and F3b and can be intercalated with the F2 facies.

Ichnology:

The bioturbation style present in F3c is similar to that observed in F3a. Moderate abundances of low diversity trace fossils inhabit the sediments in F3c. Trace fossils

observed in F3c include: *Cylindrichnus*, *Gyrolithes*, *Arenicolites*, *Skolithos*, *Planolites*, and *Teichichnus* (Fig. 2.20a). There are no examples of *Gyrolithes* Type II in these sediments. Infaunal burrowers who maintain horizontal open-tube burrows dominate the assemblage. Thicker muds are not bioturbated entirely through. Overall trace size is low indicating diminutive burrowers. Facies 3c does contain monospecific assemblages of trace fossils such as beds colonized exclusively by *Arenicolites* or *Planolites*. There is generally less bioturbation in F3c than F3b and F3a.

Interpretation:

Like F3a, F3c is interpreted to represent deposits within tidal flats. Facies 3c has a very high mud content that indicates deposition under protected, low energy conditions. The lack of significant sand interbeds indicates that this environment was not inundated with the high-energy conditions associated with F3a. Mud deposition on the tidal flat has been discussed previously in the interpretation of F3a but it is important to understand that cyclic and low-energy conditions are still expressed within F3c. This environment was somewhat sheltered from high-energy conditions but was subject to lower salinity than F3b. The standing water required for suspension deposition of these muds may have contained lower oxygen and salinity levels than mixed sediment tidal flats.

A reason for the decreased bioturbation in F3c versus F3a is the result of the increased mud deposition. Gingras *et al.* (1999a) note that the sandy tidal flats at Willapa Bay were more bioturbated than the muddy flats. This may be related to the ability of sandy substrate burrowers to rapidly rework the sediment (Swinbanks and Luternauer, 1987). Many features of the fine-grained flat deposits in the study area are very similar to the modern tidal flat deposits of The Wash in England as described by Evans (1965) and Willapa Bay in Washington State as described by Gingras *et al.* (1999a). Mud-dominated flats are characterized by low energy conditions, intertidal run-off creeks floored by fine debris lags and denoted by slightly inclined mud beds of varying bioturbation, and low sedimen-

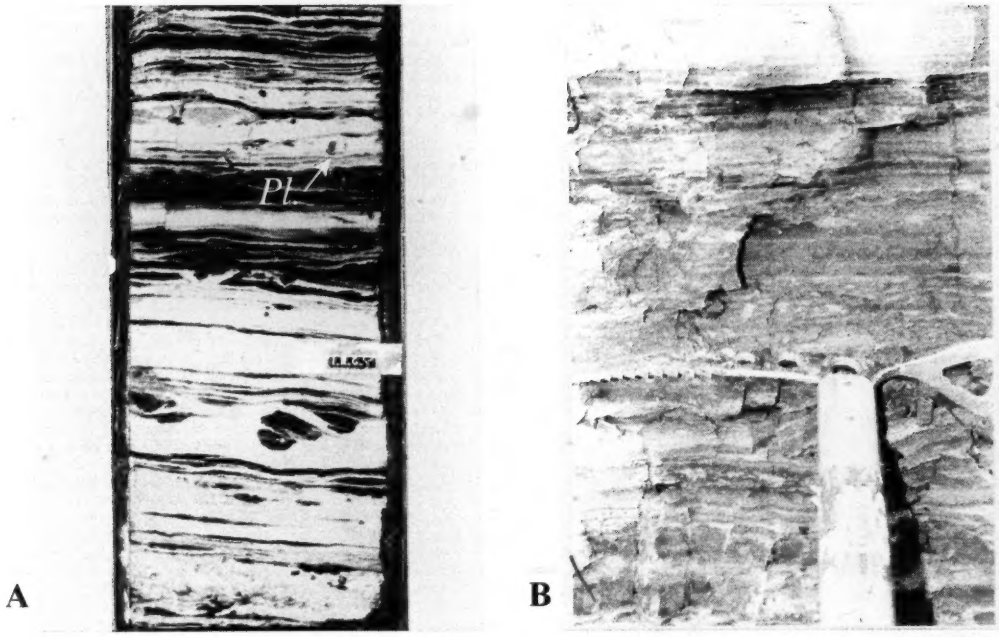


Fig. 2.20. Facies 3c. **A)** Muddy, sparsely bioturbated sediments found in core examples of F3c (5-23-95-11W4). **B)** Rare outcrop examples of F3c display a fine lamination to the mud component (E15).

tation rates.

The suggestion that not every sand and mud lamina deposited is representative of a single tidal cycle has been suggested (McCave, 1970; 1971). Dalrymple *et al.* (1991) calculated the possibility of amalgamated laminae and beds of mud and sand in Cobequid Bay, Nova Scotia. The research from flats on this macrotidal estuary indicate that mud layers less than 3mm can be deposited as a single cycle although mud laminae thicker than 3mm are most likely amalgamated depositional episodes. This evidence indicates mud laminae in F3c are deposited from both single cycle tides and amalgamated episodes.

To summarize F3c, the physical and biogenic structures indicate that this facies was deposited in a centrally located, mud-dominated estuarine tidal flat environment characterized by dynamic depositional conditions in a brackish salinity setting. The location in the estuary most apt to deposit this facies are shallow tidally-influenced bays, away from a point source of sand, and sheltered enough that mud deposition can occur by suspension.

FACIES 3D (F3D) HORIZONTALLY INTERBEDDED SAND AND MUD WITH ROBUST BIOTURBATION

Description:

Facies 3d is found in the upper sections of the McMurray Formation in this area. This facies is characterized by well-burrowed, interbedded fine-grained sand and mud (Fig. 2.21). The well-sorted sands of F3d range from lower fine- to upper very fine-grained. Grains are typically rounded to subrounded. This facies resembles other F3 facies but lacks the inclined bedding of the F2 facies. The mud contained in the interbeds of F3d is a markedly darker grey than F3c, perhaps due to differing clay concentrations in the suspended sediment or a lack of exposure. Facies 3d manifests itself as moderately burrowed, laminated to thinly interbedded sands and muds. The thickness of the individual beds in F3d is variable from 0.5 centimeter to 10 centimeters. The overall thickness of this facies can reach 5 meters. The interbeds of F3d are typically thicker than the interbeds of F3a and F3c. The sand of F3d is typically bioturbated, obscuring sedimentary structures. Sand beds where devoid of bioturbation (rare), display current and combined flow ripples with some oscillation ripples below sharp contacts with the overlying mud. Some carbonaceous debris is present separating the laminae of sand. Bedding can appear thinly laminated due to silt and rare mud laminae.

The lower contact of F3d is typically gradational. It commonly overlies F1d, and F3 facies, and is intercalated with F3e and F1d. The upper contact of F3d is also gradational with the overlying facies. Overlying facies include F3e horizontal churned beds, F1d, and the Wabiskaw member of the Clearwater Formation.

Ichnology:

Facies 3d has robust bioturbation of moderate abundance. The trace types of F3d

are of high diversity and similar in assemblage to F1d. Trace fossils present in F3d include: *Skolithos*, *Rosselia*, *Diplocraterion*, *Palaeophycus*, *Thalassinoides*, *Teichichnus*, and *Scolicia* (Fig. 2.21a). These traces do not appear in low diversity horizons or monospecific assemblages. The overall size of the trace fossils are relatively large compared to those found in F3a, F3b, and F3c. This facies does not contain escape structures.

Interpretation:

The deposits of F3d have been interpreted to represent deposition within the estuary mouth or open bay. The grain size, sorting, and alternating high-energy/low-energy bedding stratification indicate deposition in a fluctuating moderate-energy protected environment. This environment is proximal to the depositional environment of F1d. Facies 3d does contain roughly equal interbeds of bioturbated sand and mud. The appearance of the darker mud than encountered in previous facies is evidence of a relative lack of exposure to oxygen. This indicates this facies was deposited and remained subaqueous, unaffected by tidal exposure. The bioturbation of F3d is not as intense as the bioturbation found in the burrowed horizons of F1d. Traces are subjectively larger in F3d than those found in F1d.

Fluctuating cyclic conditions are indicated by the alternating sand and mud deposition. Sufficient time for reworking of the sediment by organisms is indicated by the equilibrium population bioturbate fabric of the sediment. This equilibrium population is similar to the one responsible for reworking the bioturbated intervals of F1d. This trace fossil assemblage is typical of a marine equilibrium assemblage as evidenced by the high diversity of traces and large individual sizes (MacEachern and Pemberton, 1992).

To summarize, it is evident from the physical and abundant biogenic structures that F3d was deposited in an open bay environment characterized by brackish to marine water conditions.

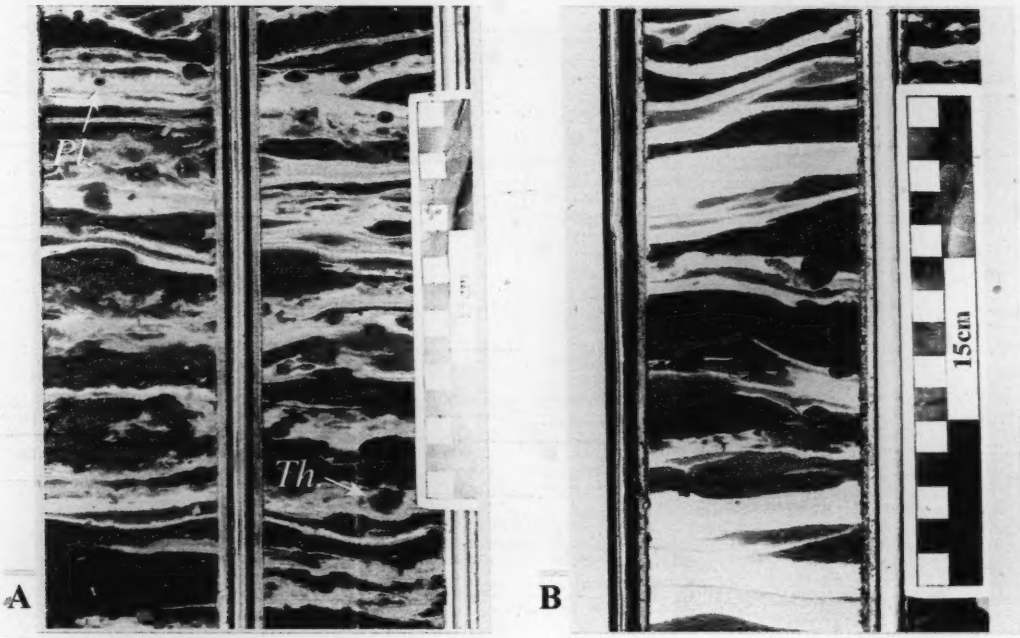


Fig. 2.21. Facies 3d. **A)** Moderately bioturbated interval including large traces such as *Thalassinoides* (Th.) (10-10-96-11W4). **B)** The wavy nature of the thicker mud beds found in F3d is apparent in core 15-9-96-11W4.

FACIES 3E (F3E) PERVASIVELY CHURNED SAND AND MUD WITH ROBUST BIOTURBATION

Description:

Facies 3e is found mainly in the upper sections of the McMurray Formation in this area. It was not observed in outcrop section. This facies is characterized by well-burrowed, fine-grained sand and mud (Fig. 2.22). The well-sorted sands of F3e range from lower fine- to upper very fine-grained. Grains are typically rounded to subrounded. The high degree of bioturbation has resulted in mixing of the mud within the sands and the obliteration of primary sedimentary structures. The mud contained in F3e is a darker grey than F3c perhaps due to differing clay concentrations in the suspended sediment or a lack of exposure similar

to F3d. The mud of F3e appears similar to the mud of F3d (Fig. 2.21). The thickness of the individual beds in F3d is uncertain due to the overall high amount of biogenic reworking of the substrate. The overall thickness of this facies can reach 5 meters. Rare interbeds of sand that appear unburrowed have a low-angle planar laminated to ripple laminated appearance (Fig. 2.22b). This is similar to the sand beds of F3d. Some carbonaceous debris is present in the churned sediment.

The lower contact of F3e is typically gradational. Facies 3e commonly overlies F1d, and F3 facies, and is intercalated with F3e and F1d. The upper contact of F3e is typically sharp except when overlain by F3d. Overlying facies include F3d horizontal interbeds, F1d, and the Wabiskaw member of the Clearwater Formation.

Ichnology:

Facies 3e has robust bioturbation with a high abundance of burrows. The trace fossil types present in F3e are of high diversity and similar in assemblage to F1d and F3d. Trace fossils present in F3e include: *Rosselia*, *Diplocraterion*, *Palaeophycus*, *Planolites*, *Thalassinoides*, *Teichichnus*, *Skolithos*, and *Scolicia* (Fig. 2.22). The overall size of the trace fossils is relatively large. Discrete trace fossils are difficult to identify due to the crosscutting nature of this bioturbate fabric. The large equilibrium suite of traces is so pervasive that any opportunistic traces are re-burrowed and no longer visible. This facies does not contain escape structures.

Interpretation:

The deposits of F3e have been interpreted to represent deposition within the estuary mouth or open bay. The grain size, sorting, and inferred primary alternating high-energy/low-energy bedding stratification indicate deposition in a low- to moderate-energy protected environment. This is similar to F1d and F3d. Facies 3e does contain roughly equal interbeds of sand and mud bioturbated into a thorough mixture. The bioturbation of

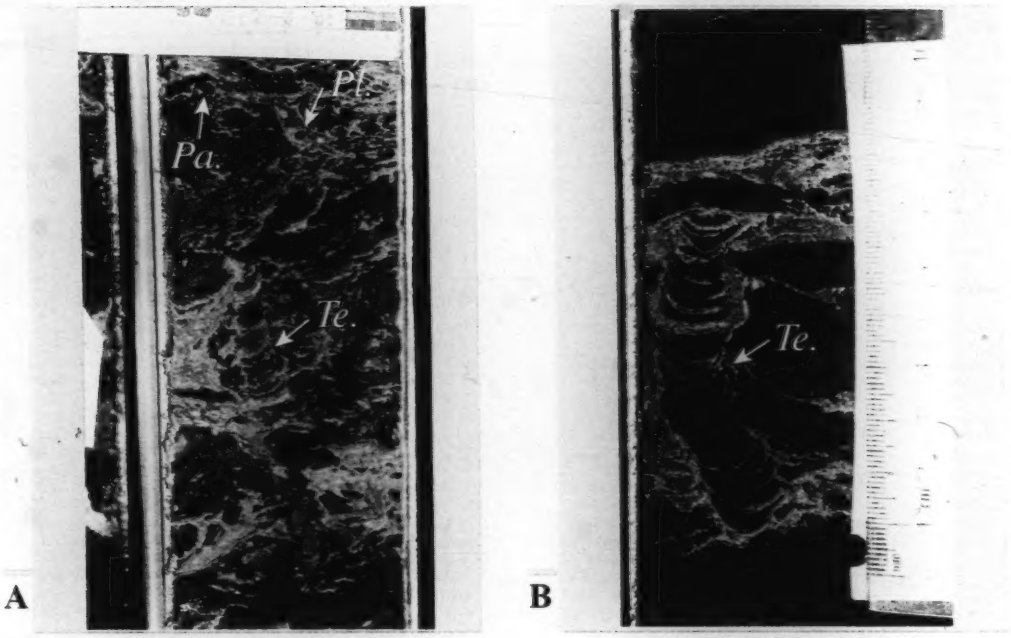


Fig. 2.22. Facies 3e. **A)** Numerous traces can be found in F3e including *Teichichnus* (Te.) and *Palaeophycus* (Pa.) (10-16-96-11W4). **B)** Some sand intervals contain planar laminated sand and are cut by intensely burrowed muddy intervals (7-10-96-11W4).

F3e is far more intense than the bioturbation found in the burrowed horizons of F1d and F3d. This is due to protection of this environment from physical reworking, and environmental physico-chemical conditions that allow increased colonization of the substrate by a diverse population. These conditions, similar to those present in the depositional environment of F3b, include: oxygen levels, salinity levels, sedimentation rates, and flow velocities. Traces are subjectively larger in F3e than those found in F1d. Similarities in grain size and trace fossil suites helps explain the gradational contacts found between F3d and F3e. The burrowing intensity of F3e indicates sufficient time for complete and thorough bioturbation of the substrate. This is dependant on low-energy conditions that prevent reworking of the sediment. It is this reworking that defines the bedding and physical structures in F1d and F3d. The muddy component of this facies most certainly represents mud originally interlaminated with the sand that has been mixed into the sand by bioturbation. This indi-

cates that F3e was deposited in a section of the estuary less prone to episodic depositional events than F1d.

The trace fossil assemblage is representative of a nearly marine assemblage. This means that the assemblage is slightly smaller and less diverse than fully marine counterparts, but far more robust and diverse than the brackish trace fossil assemblage (Pemberton *et al.*, 1982). This is consistent with the other facies know to intercalate with F3e. The trace fossil forms are clearly more diverse than those found in F2, F3a, F3b, and F3c. Facies 3b is similar in bioturbate factor but is reworked by a less diverse assemblage of smaller burrows. The increased marine influence in this environment is responsible for the diversity of forms found but not the abundance of traces. Increased burrowing intensities are a direct result of protection from significant physical reworking of the sediment by wave and tidal processes.

Gingras *et al.* (1999a) described Pleistocene quiescent bay deposits that were thoroughly mottled by bioturbation. Radiograph images of the sediments show a complete lack of vestigial laminations in the rock. Modern deposits in Willapa Bay also show intensely bioturbated fabrics in the central quiescent bay (Gingras *et al.*, 1999a).

To summarize, this bioturbated fabric is indicative of protected conditions, removed from extensive physical reworking, where mud and sand can be deposited and thoroughly reworked by organisms. The environment of deposition of facies 3e is the open bay environment, away from extensive physical reworking, and with conditions amenable to the growth and development of marine organisms. This indicates that these sediments were deposited as submarine sand bars near the estuary mouth but away from the increased current energy of the tidal inlet.

FACIES 4 (F4) HORIZONTALLY BEDDED SILTS AND MUDS

Several subfacies found in sediments of the McMurray Fm. share a common silt

to clay grain size and horizontal bedding. The subfacies are mainly found throughout the middle sections of the McMurray Fm. sediment column. The association is made up of three facies: massive to laminated grey mud (F4a), white silty mud (F4b), and dark grey carbonaceous mud with coals (F4c). With the exception of F4a, the F4 facies are rarely observed in outcrop due to the preferential weathering of outcrops containing these deposits. Only Outcrops E13 and A3 showed good examples of the F4 facies.

These facies are often found together in many core and outcrop examples. The subfacies of F4 intercalate with each other, in the overall order of F4a into F4b into F4c.

FACIES 4A (F4A) MASSIVE TO LAMINATED GREY MUD

Description:

Facies 4a is found throughout the middle section of the McMurray Formation in the Ells River area. It is characterized by thinly laminated to massive grey mud with low intensity bioturbation (Fig. 2.23). The thickness of Facies 4a is variable from 25 centimeters to 3 meters. An average thickness is roughly 50 centimeters. Facies 4a has very few small-scale physical structures and lithologic accessories. Visible sedimentary structures include flat to low-angle laminated silt and rarely, fine sand. Laminations can be lenticular to wavy while massive beds can appear mottled in core. Rooting is common with root traces typically filled with bitumen-saturated sand (Fig. 2.23b). Carbonaceous debris is also common. Incipient siderite cementation is locally observed when sufficiently compacted. Pyrite has been observed at Outcrop E16. Bioturbation is observed locally and in distinct horizons. The bioturbated horizons can be up to 1 meter thick, while thinner horizons can repeat in various thickness when separated by non-bioturbated zones of F4a.

The lower contact of F4a is gradational with Facies 2 muddy (F2c) and occasionally sandy (F2b) IHS. The upper contact can be sharp to gradational into F4b white mudstone, and can be scoured into by F1a granular sands, F1b high-angle cross-stratified sands,

and various F2 sandy facies. This facies is typically found in association with F4 muds, muddy F2c and F2f IHS, and F1a granular sands.

Ichnology:

Facies 4a does contain visible bioturbation. *Planolites* and *Teichichnus* have been observed in both core and outcrop in low abundances. Type II *Gyrolithes* have also been observed from core in this facies. Type II *Gyrolithes* have a low spiral width to length ratio. These Type II *Gyrolithes* exist in monospecific assemblages, occupying very muddy substrate that is often burrowed as deep as 15 centimeters from the sediment/water interface from which the burrows subtend. Overall bioturbation in F4a is low.

Interpretation:

The deposits of F4a have been interpreted to represent channel cut-off and abandonment muds. The deposition of thick muds requires an environment of sufficiently low flow velocities and fine-grained sediment load. Locations of such conditions that can be proximal with other associated facies include: 1) channel abandonment fill; 2) chutes or swales along a point bar; and 3) oxbow lakes or ponds. The documented 3-meter thickness of this facies eliminates the possibility of deposition from a flooding event as a probable mechanism of deposition. The overall thickness of such a deposit, and the likelihood of low preservation rule out deposition from an event deposit.

Channel abandonment in a meandering fluvial to estuarine system is the direct result of the cut-off of meanders. Reineck and Singh (1980), Harms *et al.* (1982), and Miall (1996) described two possible processes for channel abandonment: 1) chute cut-off or 2) neck cut-off (Fig. 2.24). The difference between the two types is reflected in where the channel is cut off on the meander loop. Chute cut-off is the result of a new channel carving a chute on the point bar while neck cut-off results from cut-off at the narrow neck between two meanders. Chute cut-off results in a succession that has thinner mud deposits

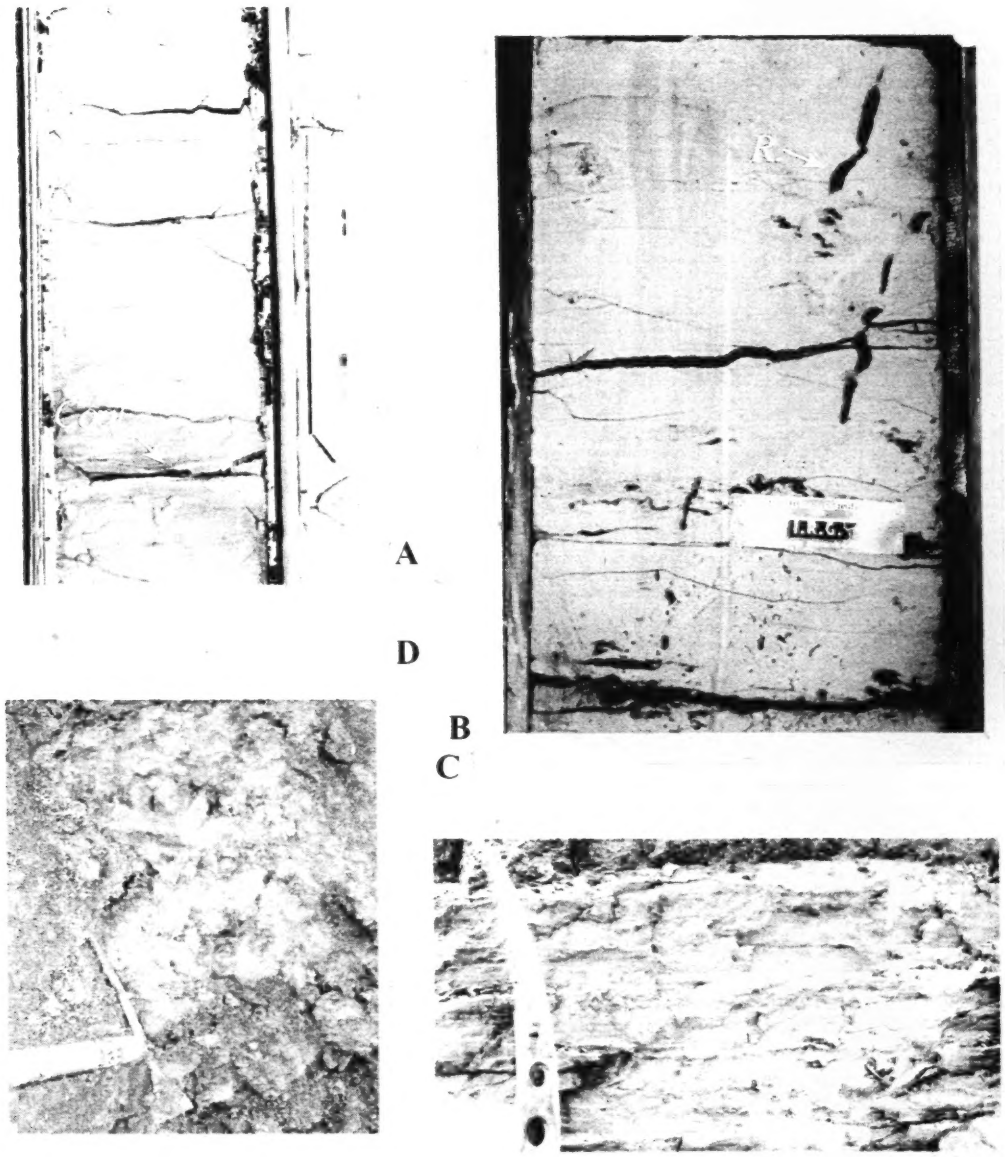


Fig. 2.23. Facies 4a. **A)** The mud of F4a may appear massive but does contain thin laminations. Coal debris defines the laminations here (10-10-96-11W4). **B)** Sand infills the root traces left after the organic material has decayed (11-3-96-11W4). **C)** Laminations in F4a seen in outcrop (E14). **D)** Outcrop E15 along the Ells river displays poor preservation of this recessive facies.

and thicker underlying coarse-grained deposits (F2b) (Reineck and Singh, 1980; Boggs, 1995). This cut-off type is more reflective of the thickness of this facies in this area and the interaction of this facies with associated facies environments.

Facies 4a has a relative paucity of trace fossils, a result of this type of restricted depositional environment. Chute cut-off abandonment channels can sustain biological organisms towards the termination of the channel and to an extent after total separation from the circulating water flow. It is also probable that episodic flooding of this low area may be a factor in bioturbation. It is this water flow with its oxygen and nutrients that marine organisms need to survive in an environment. *Gyrolithes* Type (II) assemblages may again indicate the stressed nature of this environment (Beynon and Pemberton, 1992) due to their escape abilities (Bechtel, 1996).

To summarize F4a, it is evident from the physical and biogenic structures that this facies was deposited in a mud-dominated channel abandonment fill setting characterized by exceptionally quiescent depositional conditions of low salinity.

FACIES 4B (F4B) WHITE SILTY MUD

Description:

Facies 4b occurs through the middle section of the McMurray Formation in this area. Here it is characterized as a massive to laminated, white to light gray mud of high clay content (Fig. 2.25). It is variably compacted and locally cemented. Facies 4b has some small-scale physical structures and lithologic accessories. Rooting is common with root traces typically filled with carbonaceous mud (Fig. 2.25). Carbonaceous debris is also common throughout the massive and laminated zones of this facies (Fig. 2.25c). Siderite cement is locally present; disseminated nodules of pyrite are found throughout the facies. Facies 4b displays common occurrences of paleosol development as evidenced by white colored mud and pyritized organic material (Fig. 2.25d). With the exception of core 14-23-

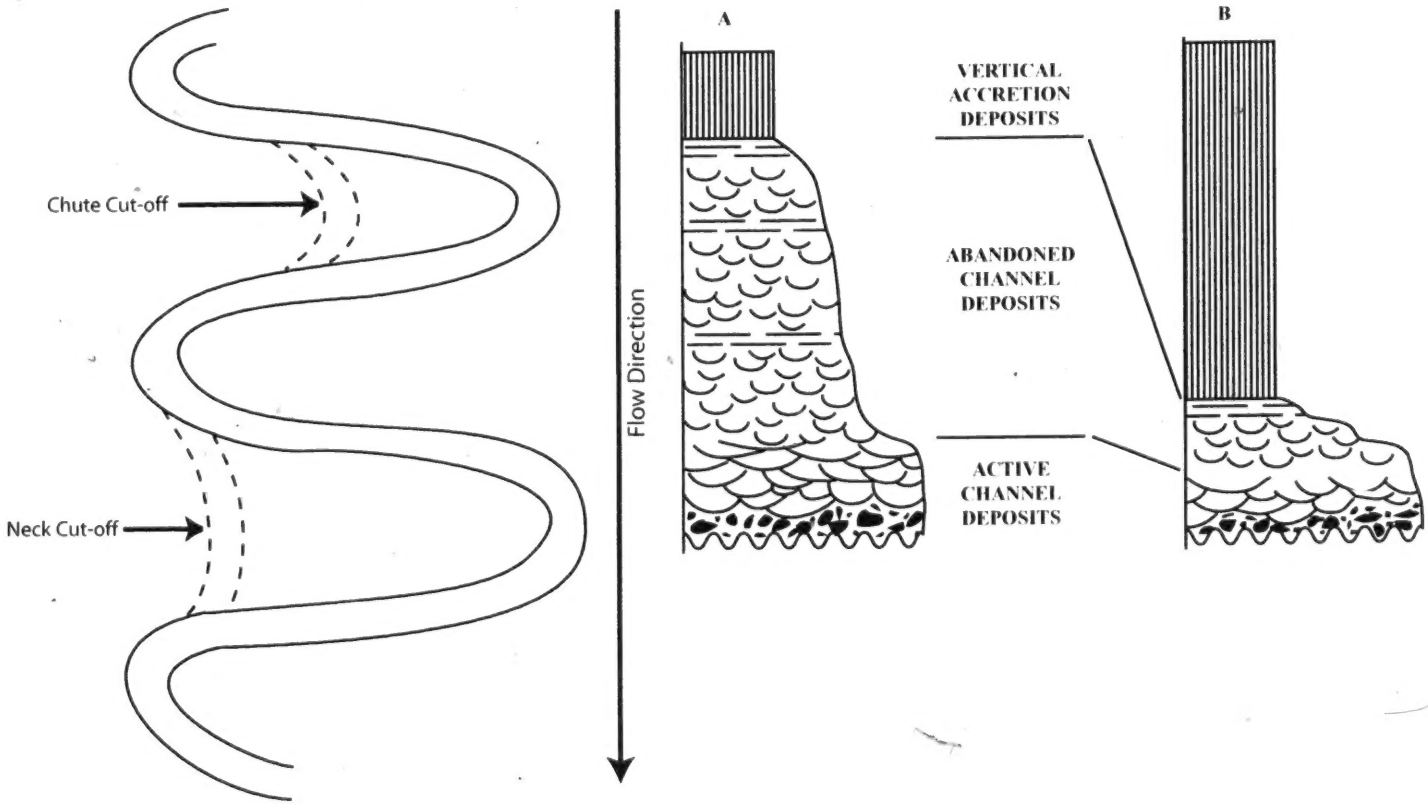


Fig. 2.24. Meander loops abandoned by chute cut-off and neck cut-off. Dashed lines indicate new channels. A) Idealized vertical succession in a chute cut-off. B) Idealizedvertical succession in a neck cut-off (modified from Harms et al., 1982)

95-11W4, and the physical disruption of roots, the sediments are unbioturbated.

The lower contact of F4b is gradational with F4a muds. The upper contact can be sharp to gradational into F4c dark muds and can be scoured into by F1a granular sands. Facies 4b often intercalates with F4c. This facies is typically found in association with F4 muds, and F1a granular sands.

Ichnology:

One example from a light gray mud in core 14-23-95-11W4 was bioturbated by diminutive traces of *Planolites* and *Teichichnus* (Fig. 2.25b). These traces were limited to a zone less than 10 centimeters in thickness. No other core or outcrop examples were found containing bioturbated intervals of this facies.

Interpretation:

The deposits of F4b have been interpreted to represent flood basin sediments adjacent to a fluvial channel system. Mud sized particles have low settling velocities and as such require very low energy conditions for deposition. Flood basin deposits are the result of suspension deposition by overbank flows (Boggs, 1995). The decrease in velocity is the result of unconfined flow moving away from the channel. Fine-sediment laden standing water also results in mud deposition from evaporation or gradual draining.

The flood basin is a site for pedogenic soil formation due the lack of coarse-grained input and rare inundation (Collinson, 1986). Light grey to white coloring, rooting, carbonaceous debris, pyrite nodules, and siderite nodules are evidence of subaerial exposure and soil formation under humid conditions (Walker and Cant, 1984; Collinson, 1986; Retallack, 1990).

To summarize F4b, the physical structures indicate that this environment formed in a dry to shallow-water setting of very stressed conditions with some salinity. The white mud indicates exposure and the roots indicate sufficient air and sunlight for plant growth. These

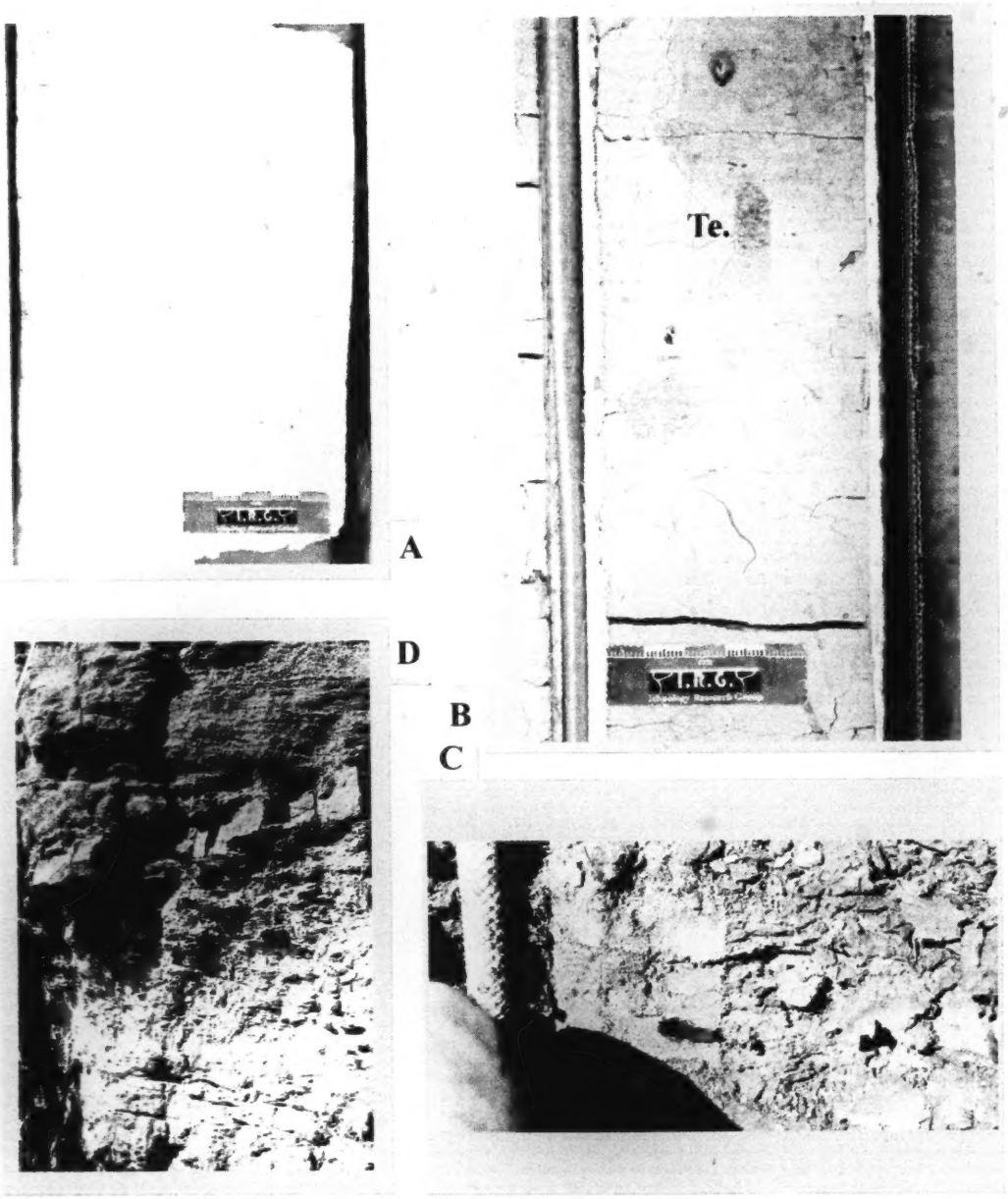


Fig. 2.25. Facies 4b. **A)** White mud in core 10-3-96-11W4. **B)** Rare trace fossils have been identified in core 14-23-95-11W4. *Teichichnus* (Te.) is observed in this core. **C)** Carbonaceous debris of various sizes is common in F4b (E14). **D)** The upper surface of F4b is commonly scoured by sand (A1).

features are found high on exposed flood basin settings at a sufficient distance from the active channel.

FACIES 4C (F4C) DARK GREY CARBONACEOUS MUD WITH COALS

Description:

Facies 4c is only found in the middle section of the McMurray Formation in the study area. It is characterized as a massive, dark gray mud of high carbonaceous content, which lends the mud its dark color (Fig. 2.26). Facies 4c may locally contain sand and silt laminae, and is typically poorly cemented due to the high organic content. This facies contains small-scale physical structures and lithologic accessories. Facies 4c is the only facies in the study area to contain bedded (*in-situ*) coals (Fi.g 2.26d). Coal beds found in F4c may be up to 2 meters thick. Rooting is common with root traces typically filled with carbonaceous mud (Fig. 2.26a). Carbonaceous debris, coal fragments, wood fragments, dispersed sand grains, concretions, and mud clasts are sporadically distributed throughout F4c. Siderite cement is seen less frequently than with F4b; F4c contains more nodules of pyrite. There is no bioturbation associated with this facies.

The lower contact of F4c is generally sharp with F4b, however, at core 10-3-96-11W4 it has been characterized as a gradational contact due to intercalation. In all cases of F4c, it directly overlies F4b. The upper contact is consistently sharp to scoured into by F2 IHS sediments and can be scoured into by F1a granular sands (Fig. 2.26c). This facies is typically found in association with F2 facies, F4a, F4b, and F1a.

Interpretation:

The deposits of F4c have been interpreted as a swamp environment related to the flood basin deposits of F4b. Both facies contain mud-sized particles of low settling velocities, requiring very low energy conditions for deposition. The abundant organic matter and

carbonaceous debris indicate deposition proximal to a well-vegetated environment capable of sourcing sufficient organics. The inclusion of dispersed sand grains and rare mud clasts are the result of vegetative baffling of the incoming overbank flows. Laminated concretions commonly composed of siderite are indicative of soil development related to the floodplain (Retallack, 1990).

Coal beds are an associated deposit due to the formation of peat swamps in the marsh environment. Blatt (1982) noted that the requirements for forming peat deposits were three-fold: 1) slow, continuous rise in ground water, 2) protection of the peat swamp from marine inundations and fluvial floods, and 3) an area of low relief remaining free of fluvial sediment input, to prevent interruption of the peat forming process. For coal to be preserved the accumulation of organic matter must supercede the decomposition of the organic material due to microbial and chemical processes. Soils alone are difficult to form as sedimentation rates often preclude their development (Kraus and Aslan, 1993). Flood basin deposits with marsh environments are a suitable area for formation of peat swamps due to the sufficient plant material, wet conditions, and local subsidence from the addition of fluvial sediment.

This facies formed on the flood basin where sufficient distance from active sedimentation near the channel allowed for the formation of flora while a slow rise in the water table provided preservation of the organic material as coal.

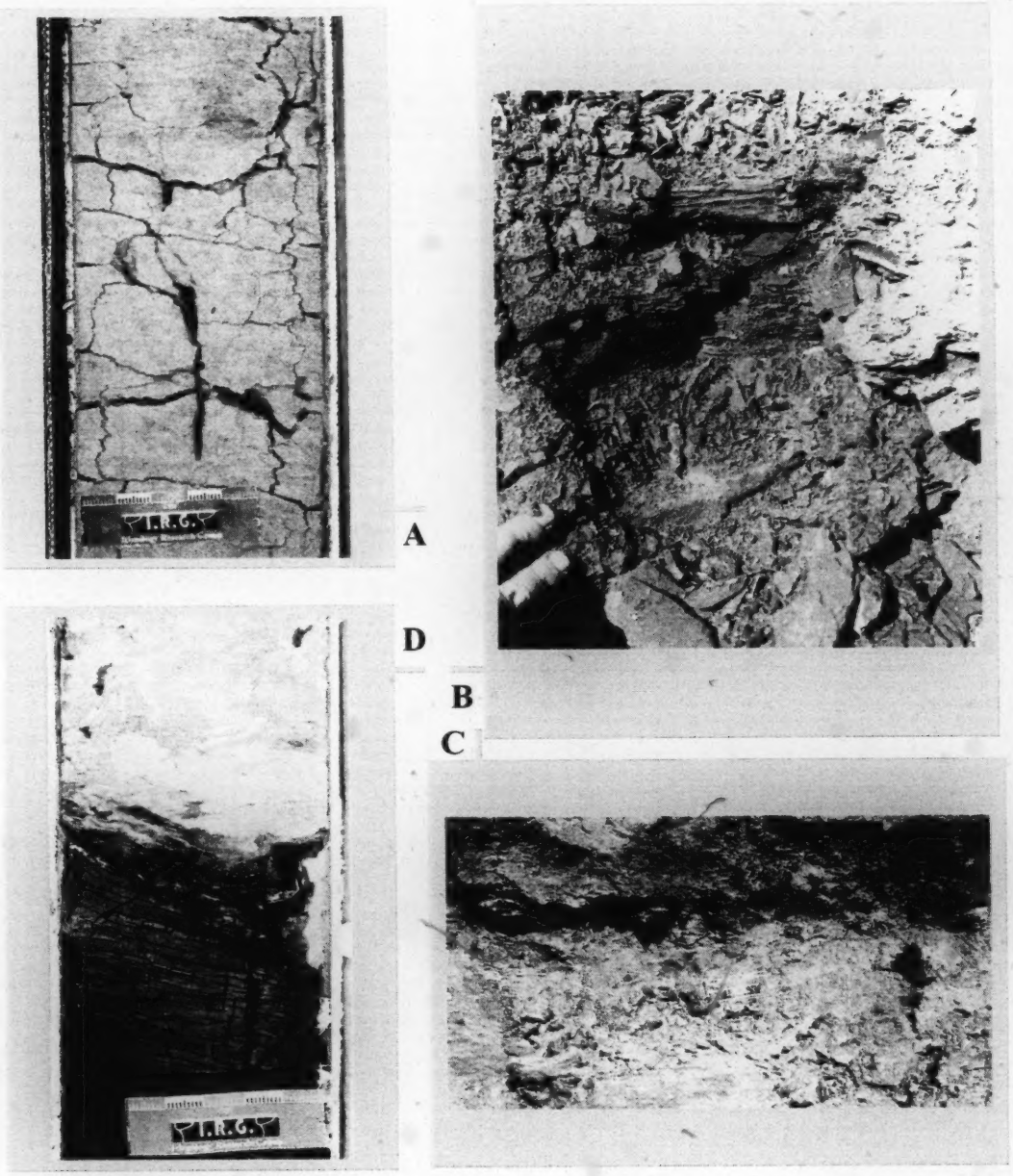


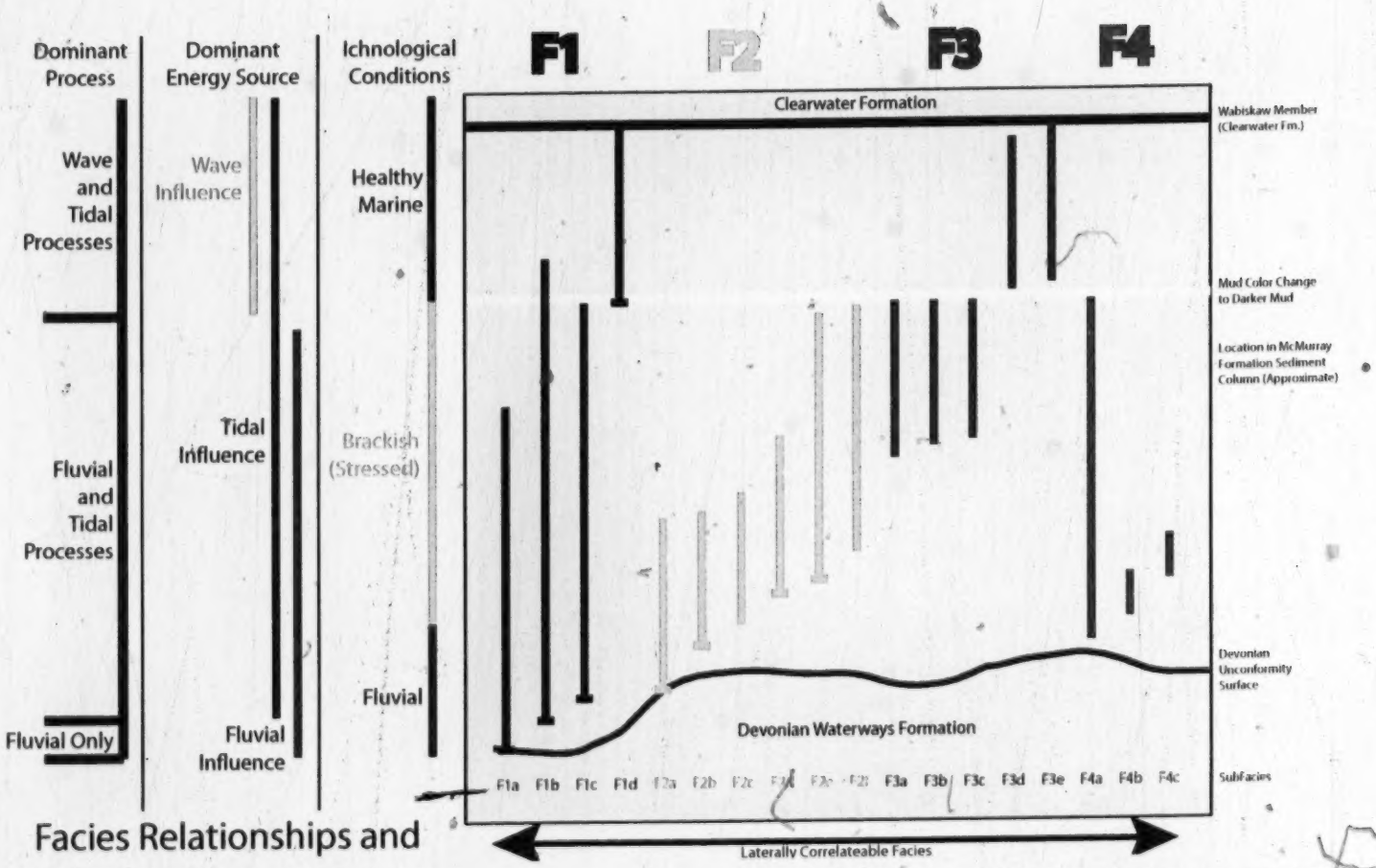
Fig. 2.26. Facies 4c. **A)** Sideritized root traces are common (11-3-96-11W4). **B)** Bedded coal and highly organic clay at outcrop E14. **C)** Weathered F4c in outcrop cut by bitumen saturated sands (E14). **D)** Coal beds are common and observed to be *in-situ* exclusively in F4c (10-3-96-11W4).

FACIES ASSOCIATION INTERPRETATION

Facies identified in the facies description component of this study have been grouped into facies associations. This provides a significant framework for interpretation of the McMurray Formation in the Ells River area. The high variability of the McMurray Formation noted by Carrigy (1959; 1967; 1971; 1973a) and various other authors (Flach, 1977; Mossop and Flach, 1983; Ranger and Pemberton, 1992; 1997; Yuill, 1995; Bechtel, 1996; Wightman and Pemberton, 1997; Hein *et al.*, 2000) requires this approach to the characterization of the depositional environments.

Interpreting the vertical succession in core and outcrop requires precise application of Johannes Walther's Law of the Correlation of Facies (Walther's Law). Walker (1992) paraphrased the law as "in a vertical succession, a gradational transition from one facies to another implies the two facies represent environments that were once adjacent laterally". The facies described earlier are shown in lateral relationship to each other in figure 2.27. This diagram does not account for homotaxy that may exist between the different facies and their stratigraphic environment of deposition. Facies associations in this study are an attempt to group related facies in order to recognize genetically related deposits. Identification of discontinuities between these facies associations is equally as essential for a full interpretation of the stratigraphic succession.

The following discussions interpret the facies associations as genetically related units with a detailed characterization and interpretation of bounding discontinuities. The facies associations are not presented in the three-fold subdivision of the McMurray developed by Carrigy (1959) and subsequently used by researchers conducting work in the McMurray Formation. The results of this study do not clearly endorse this subdivision and as such, it would be improper to utilize the associated terminology for interpretation. The facies associations are presented in a genetic stratigraphic context, thus sequence stratigraphic terminology will be applied where appropriate. Figure 2.28 is a schematic



Facies Relationships and

Fig. 2.27. The lateral relationships between facies observed in outcrop and core. The relationship of facies to dominant energy source, processes, and environmental characteristics are shown. This diagram does not insinuate a homotaxy but rather a vertical section relationship hung from the base of the Wabiskaw member.

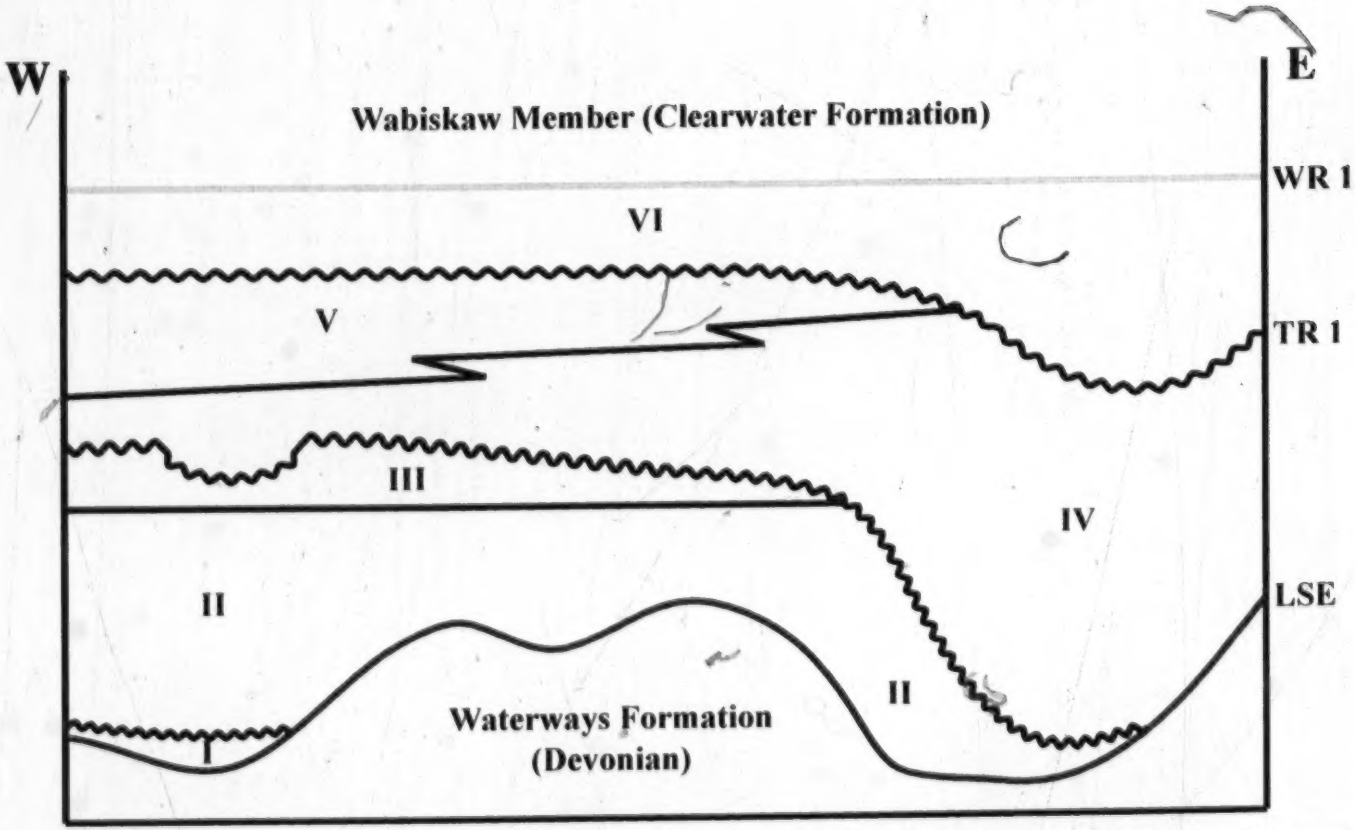


Fig. 2.28. Schematic east-west cross-section through the McMurray Formation in the study area relating the facies associations to the major surfaces encountered. Facies associations are shown in roman numerals. The sequence of deposition begins on the Lowstand Surface of Erosion (LSE) while the Tidal Ravinement Surface (TR1) separates Facies Association 6 from Facies Association 5 and the Wave Ravinement Surface (WR1)(Datum) represents the end of McMurray deposition.

stratigraphic cross-section of the McMurray Fm. in the Ells River area that displays the vertical succession of the facies associations and the nature of their bounding discontinuities. Facies Association 1 (FA1) is found within the lower portion of the McMurray Fm. sedimentary succession while Facies Association 6 (FA6) is found in the upper sections of the McMurray Fm. The facies associations will be discussed in the general vertical order in which they occur from bottom to top.

The facies associations and their bounding discontinuities allow for the separation of the McMurray Formation in this area into a distinct, unconformity bounded lower-order sequence as defined through sequence stratigraphy. The contact between the McMurray Formation and the Clearwater Formation is not interpreted as a sequence boundary in this area.

SUB-CRETACEOUS UNCONFORMITY

The McMurray Formation in the vicinity of the Ells River unconformably overlies Devonian carbonates (Fig. 2.5). During the depositional hiatus before the late Aptian, the top of the Devonian was subjected to periods of subaerial erosion (Carrigy, 1963a; Stewart, 1963). This is a high relief surface with gradients as high as 75 m/km (Bechtel, 1996). In the study area, the Devonian surface displays a depositional gradient of nearly 60 m/km. Evidence of paleosol generation is commonly observed in core along this surface (Fig. 2.29) where abundant iron staining and high amounts of pyrite are present.

Reinson (1992) noted the importance of a basal unconformity when interpreting estuarine systems. Estuaries occur in a transgressive environment and as such, should directly overly a regional unconformity. This is important when attempting to place the deposits in a sequence stratigraphic framework.

The Devonian surface marks the lowermost bounding discontinuity of the McMurray succession. Exposure and erosion of the Devonian carbonates is a result of relative

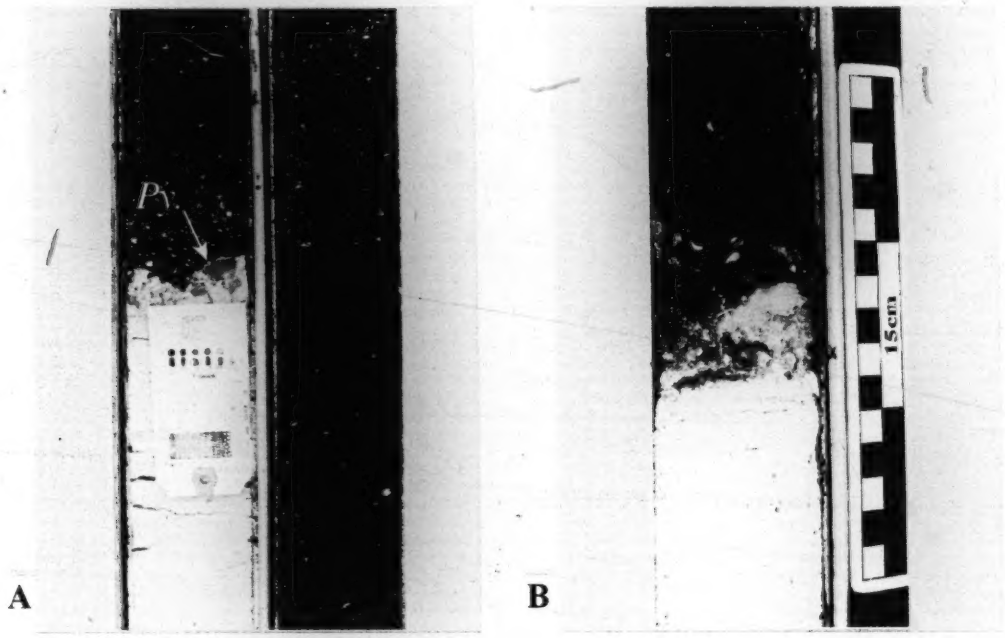


Fig. 2.29. A) The sub-Cretaceous unconformity exposes Devonian Waterways Formation that is weathered and commonly the site of pyrite (Py.) formation. **B)** The contact is sharp and overlain by coarse sand.

sea level drop due to tectonic uplift in the area. The unconformity in this area represents the Mannville Group lower boundary and also the lowstand surface of erosion (LSE)(Fig. 2.29).

DEFINITION OF AN ESTUARY

The definition of an estuary is variable and problematic for a variety of reasons. A scientific definition of an estuary was proposed by Dalrymple *et al.*, (1992). The definition states that an estuary is "the seaward portion of a drowned river valley system which receives sediment from both fluvial and marine sources and which contains facies influenced by tide, wave, and fluvial processes. The estuary is considered to extend from the landward limit of tidal facies to the seaward limit of coastal facies at its mouth". Dalrymple

et al. (1992) also note that estuaries can only form as the result of a relative sea-level rise.

Recognizing the morphological zonation of an estuary in the rock record is complex, but very necessary for properly interpreting estuarine sediments. Many terms used to describe the various parts of an estuary have been published (Dorjes and Howard, 1975; Smith, 1987; Allen, 1991; Dalrymple *et al.*, 1992; Allen and Posamentier, 1994). A selection of these terms is given in figure 2.30. One of the most significant studies is the estuary classification paper of Dalrymple *et al.* (1992). The authors suggest that estuary classification and terminology be standardized, and propose an estuary classification continuum that has wave-dominated and tide-dominated as end-members. This classification represents the dominant energy source present at the marine end of the estuary (Zaitlin *et al.*, 1994). The estuary can be divided into a tripartite zonation: 1) an inner or upper, river-dominated zone; 2) a relatively low energy central/middle zone where marine energy is approximately balanced with fluvial energy; and 3) an outer or lower zone dominated by marine processes (Dalrymple *et al.*, 1992; Zaitlin *et al.*, 1994). A fine-tuned diagram based on the conclusions of Dalrymple *et al.* (1992) and relating explicitly to the McMurray Formation is given in Figure 2.31. Figure 2.30 shows the correlation of estuarine morphology terms used by authors referenced in this study. Evidence from this study indicates the McMurray Formation formed as a strongly tide-influenced estuarine system.

FACIES ASSOCIATION 1 (FA1)

Facies Association 1 is a locally present facies association commonly found at the base of cores that penetrate lows along the sub-Cretaceous unconformity. Along this unconformity, FA1 consists of F1a (Granular Grading Sand), F1b (Large Scale Cross-Stratified Sand), and F4a (Grey Structureless Mud). This facies association is comprised of mainly one facies (F1a) with occurrences of a second and third facies (F1b, F4a). Facies 4a typically overlies F1b with a sharp to gradational (over 10cm) contact. FA1 is charac-

Dalrymple et al., (1992) Facies Model	General	Outer	Central	Inner
MacEachern and Pemberton (1994) Viking Formation	Wave Dominated	Estuary Mouth Complex	Central Basin Complex	Bay-Head Delta Complex
Dalrymple et al., (1992) Facies Model	Wave-Dominated	Barrier/Inlet	Central Basin	Bay-Head Delta
Allen and Posamentier (1994) Gironde Estuary	Mixed-Energy	Estuary Mouth	Inner Estuary	
Allen (1991) Gironde Estuary	Mixed-Energy	Inlet	Estuarine Funnel	Upper Estuary Channel
Dorjes and Howard (1975) Ogeechee River/ Ossabaw Sound	Mixed-Energy	Lower-Middle	Upper-Middle	Inner
Smith (1988b) Willapa and Daule-Babahovo Rivers	Mixed-Energy?	Lower	Middle	Upper
Dalrymple et al., (1992) Facies Model	Tide-Dominated	Sand Bars/Flats	Tidal Meanders	Tidal-Fluvial

Fig. 2.30. A comparison of terms for different regions of an estuary as defined by the referenced authors (modified from Bechtel, 1996).

terized by granular sand, normally grading and repeating above a sharp incision into the sub-Cretaceous unconformity (Fig. 2.29). The upper contact of this facies association is scoured by the basal sediments of Facies Association 2 (FA2) or in the upper sections by Facies Association 4 (FA4). This facies association is localized and scoured into by the overlying deposits.

F1a represents initial sediment deposition in channelized environments under high-energy conditions. The muds of F4a when preserved are interpreted to indicate regional ponding, channel abandonment, or flood basin deposits. This facies association contains

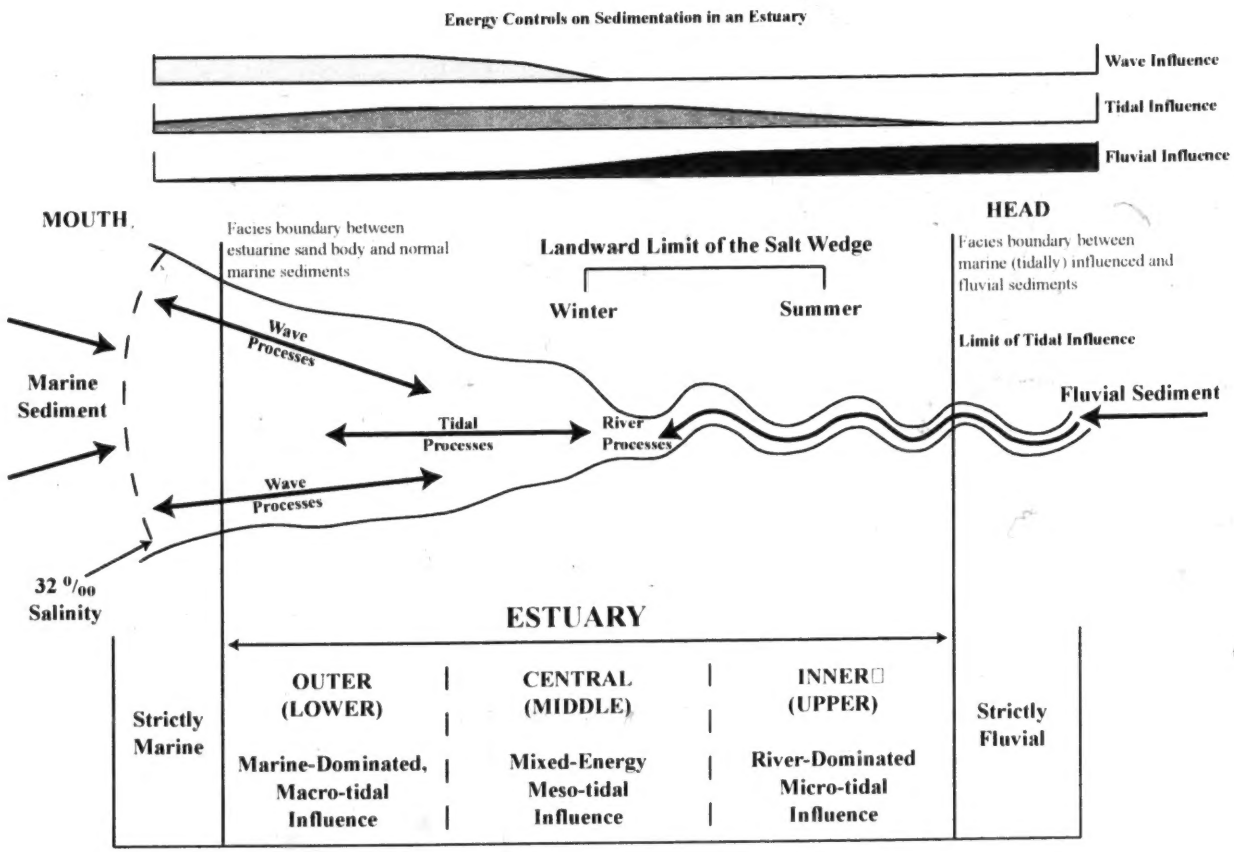


Fig. 2.31. The geographic zonation of an estuary and the environmental processes and characteristics that affect estuary conditions and sedimentation.

no bioturbation and no tidal indicators. Normal grading that directly overlies a significant lag layer is similar to that observed in the braided systems of the Battery Point Formation, Quebec (Miall, 1978). Often the grading is repeated in vertical succession with or without the interspersed high-angle bedding of F1b. Accretion bars show internal structures dominated by tabular and trough cross-bedded sands that grade from gravel to fine sand. The grain-striped pattern of the inclined sediments are indicative of avalanche flow down the lee side of a subaqueous dune. The bar deposits found in FA1 represent downstream accretion of sediments by avalanche sedimentation on two-dimensional or three-dimensional bar forms. The angular grains, poorly- to moderately-sorted nature, and coarse grain size further support the interpretation of basal deposition in a fluvial channel.

It is interpreted that this facies association best represents deposition in a braided fluvial system which is gradually becoming a meandering system (Fig. 2.32). The abundance of coarse grains, lack of epsilon cross-stratified material, and position immediately above local lows in the sub-Cretaceous unconformity indicate a channel environment within confined conditions subject to a high variation in depositional energy and flow. Due to the coarse-grained sediments, FA1 is interpreted to represent bedload deposition (Schumm, 1981).

Variable discharge in the early Cretaceous, as fluvial systems attempted to define a significant trunk drainage system throughout an area controlled by erosional surfaces incising the exposed Devonian sediments, gives paleogeographic evidence for a braided system. With highly erodable banks composed of granular sand, sinuosity is relatively low with very little meander development. The lack of previously deposited sediments to develop bank walls capable of supporting a meandering system, and the hard, variably eroded but shallow setting of the hinterland indicate that the early sediments were deposited as braided to slightly sinuous channel fill (Fig. 2.32).

Cant (1982) identified several characteristics that promote the development of a braided system: 1) rapid fluctuations in fluvial discharge; 2) an abundance of coarse sedi-

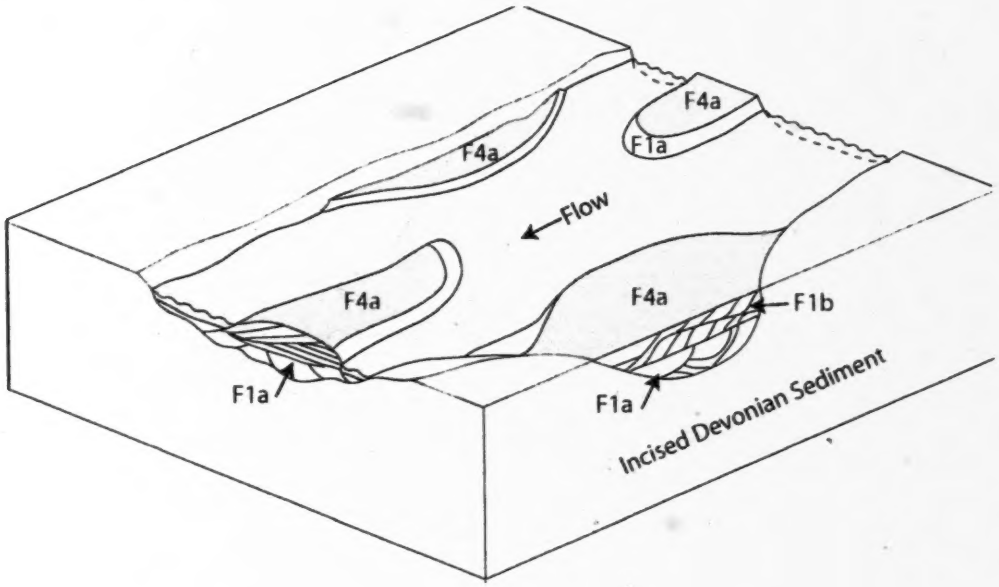


Fig. 2.32. Block diagram of the braided fluvial depositional system responsible for depositing Facies Association 1. Note the sharp erosion surface with the exposed Devonian material (grey) and the complex way that the fluvial bars deposit the sand beneath the thin layer of suspension deposited mud (brown).

ment; 3) a high rate of sediment supply; and 4) easily erodable, non-cohesive banks. These features are all present in the sediments or the character of deposition of Facies Association 1. Braided river deposits often comprise mid-channel bars that are oriented longitudinal to flow, repeating in vertical succession (Miall, 1996). Longitudinal bars described by Galloway and Hobday (1983) show a vertical succession where lags and high-angle beds of coarse sand are immediately overlain by a thin veneer of silt and mud. This thin veneer of silt and mud is similar to the deposits of F4a in this environment. As braided systems are more common on steep or uneven continental slopes than meandering systems, and are commonly subject to more rapid fluctuations in flow, braided systems often develop into meandering systems when the slope angle and overall flow velocity become amenable

to increased sinuosity and the development of meanders (Boggs, 1995). The sometimes gradational relationship of FA1 to FA2 indicates such a transition.

This facies association is interpreted to represent initial deposition within the valley complex in this area. This facies association indicates strictly fluvial deposition representative of sedimentation in a progradational lowstand systems tract (LST).

FACIES ASSOCIATION 2 (FA2)

Facies Association 2 is characterized by a fining-upward succession. This facies association is comprised of facies F1a, F1b, F1c, F2a, F2b, F2c, and F4a. It typically has a granular to sandy base and fines to mud in the upper portions in the study area. FA2 is commonly the first association above the sub-Cretaceous unconformity except where underlain by FA1. The examples of FA2 are limited to lows on the sub-Cretaceous unconformity where they exist in a complete sequence. These deposits are also commonly eroded by the depositional systems of FA4. Thinner examples of FA2 can be found on the flanks of paleo-geographic highs on the Devonian surface where incomplete successions are commonplace.

The complete succession of FA2 occurs in a predictable order. Granular graded sand (F1a) overlies a sharp erosional contact either with the Devonian surface or underlying McMurray sediments. This facies grades into high-angle cross-stratified sand (F1b) followed by the overlying small-scale cross-stratified sand (F1c). Locally the sediments overlying F1c represent intercalated sand-dominated IHS (F2b) and mudclast breccia in inclined sand (F2a). Typically the sand-dominated IHS (F2b) fines upwards into mud-dominated IHS (F2c). In an uninterrupted succession the column is capped by massive grey mud (F4a). Bioturbation is rare to absent in all of these facies, a characteristic of FA2. All facies with the exception of F1a display tidal signatures.

In many occurrences of this facies association, particularly flanking Devonian

highs, entire facies are absent. The fining upward character in this association however is not disrupted by missing facies. An example from core 5-23-95-11W4 contains a vertical succession of FA2 consisting of F1a, F2b, F2c, and F4a respectively (Fig. 2.33). This is a preservational variant of FA2 due to a lack of accommodation space. The vertically repeating examples of FA2 represent stacked channels migrating across the depositional area, cutting into or preserving the upper facies of FA2.

The succession of FA2 represents deposition within an increasingly tidally influenced meandering channel environment of very low salinity (Fig. 2.34). The sharp erosional surface consistently found at the base of FA2 corresponds to channel erosion and incision from lateral migration. The granular grading sands of F1a represent the initial channel fill under high-energy conditions. The high-angle cross-stratified sands of F1b that overlie F1a were deposited as subaqueous dunes migrating within the channel. Small-scale cross-stratified sand (F1c) was deposited under significantly lower energy flow conditions on larger channel bedforms such as the subtidal bars of F1b. Examples of sand-dominated IHS (F2b) that overly F1c in this area are the result of deposition on laterally accreting point bar surfaces in a meandering tidally influenced channel. The fining upward of F2b into the muddy IHS of F2c indicates lower energy conditions in the meandering channel environment. These mud-dominated IHS sediments accumulate as laterally accreting point bar deposits. The capping of this succession by grey mud (F4a) is the result of suspension deposition from low flow conditions associated with individual channel abandonment.

The fining succession, tidal signature, paucity of burrowing, and association with the overlying rooted and carbonaceous deposits of Facies Association 3 suggest an environment of fresh water and fluvial processes for FA2 (Fig. 2.34). This interpretation is further supported by palynological evidence obtained from fining upward unbioturbated successions immediately above the sub-Cretaceous unconformity indicating fresh water conditions with rare brackish water influences (Flach, 1984).

Typical examples of FA2 are characterized by sand units that fine-upwards from

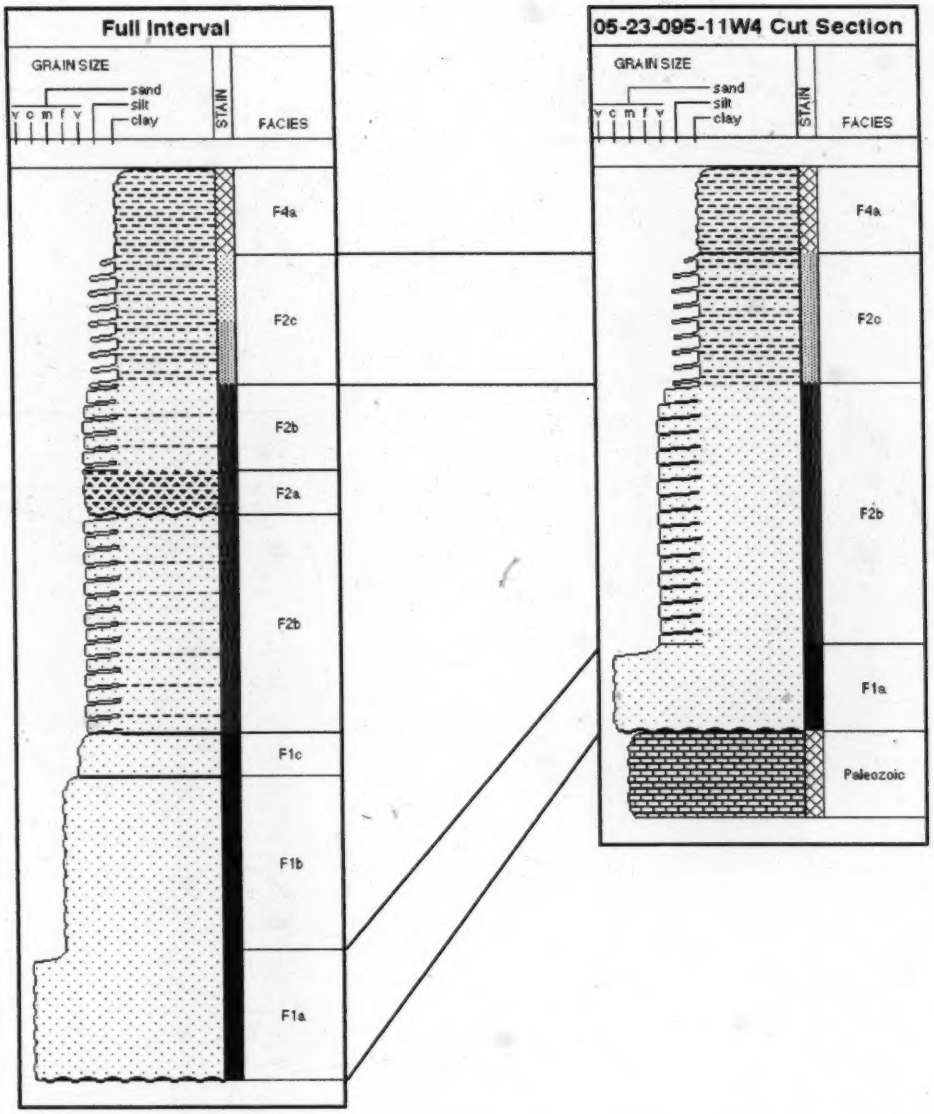


Fig. 2.33. Various preservation styles observed for Facies Association 2. The section at left is a composite of the full interval encountered in FA2 including Facies 1b, 1c, and 2a. The core from well 05-23-095-11W4 at right signals deposition on a paleo high as indicated by the lack of Facies Association 1 between FA2 and the sub-Cretaceous unconformity.

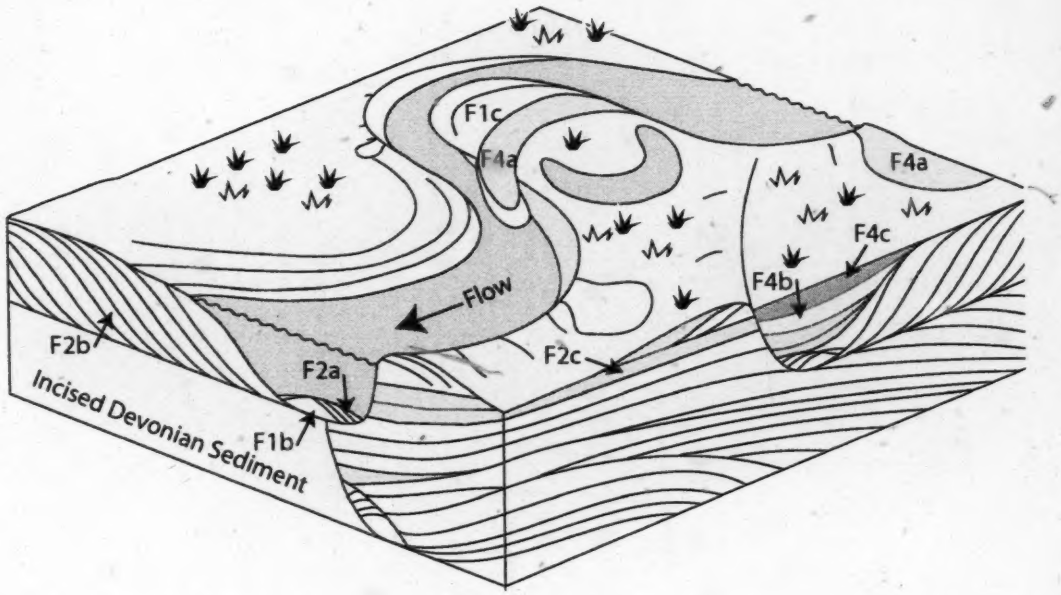


Fig. 2.34. Block model diagram of the type of meandering fluvial system responsible for the deposition of Facies Associations 2 and 3. The cross-cutting nature of the FA2 sands fining into channel cut-off muds with overlying floodplain (FA3) is shown above. The mud-dominated facies of F4b and F4c are seen at right colored grey and black respectively. Note the Inclined Heterolithic Stratification that develops as the major sand deposit in this environment.

coarse- or medium-grained, granular sand to high-angle cross-stratified sand to small-scale cross-stratified sand to sand-dominated IHS which then pass abruptly into mud-dominated IHS and grey mud. Smith (1987) defined a point bar model for different meandering river conditions. He identified a threefold subdivision that represented the various processes and sediments that occurred within point bars as a result of increased tidal influence (Fig. 2.35). The three point bar types, presented landward to seaward, are: 1) fluvial sandy point bar facies; 2) low-energy fluvial sandy point bar facies; and 3) mesotidally influenced point bar facies deposited in upper and middle estuary settings. Using this classification, the profile of FA2 would correspond to a mix of low energy fluvial to mesotidally influenced point bar facies dependant on the amount of capping mud-dominated IHS

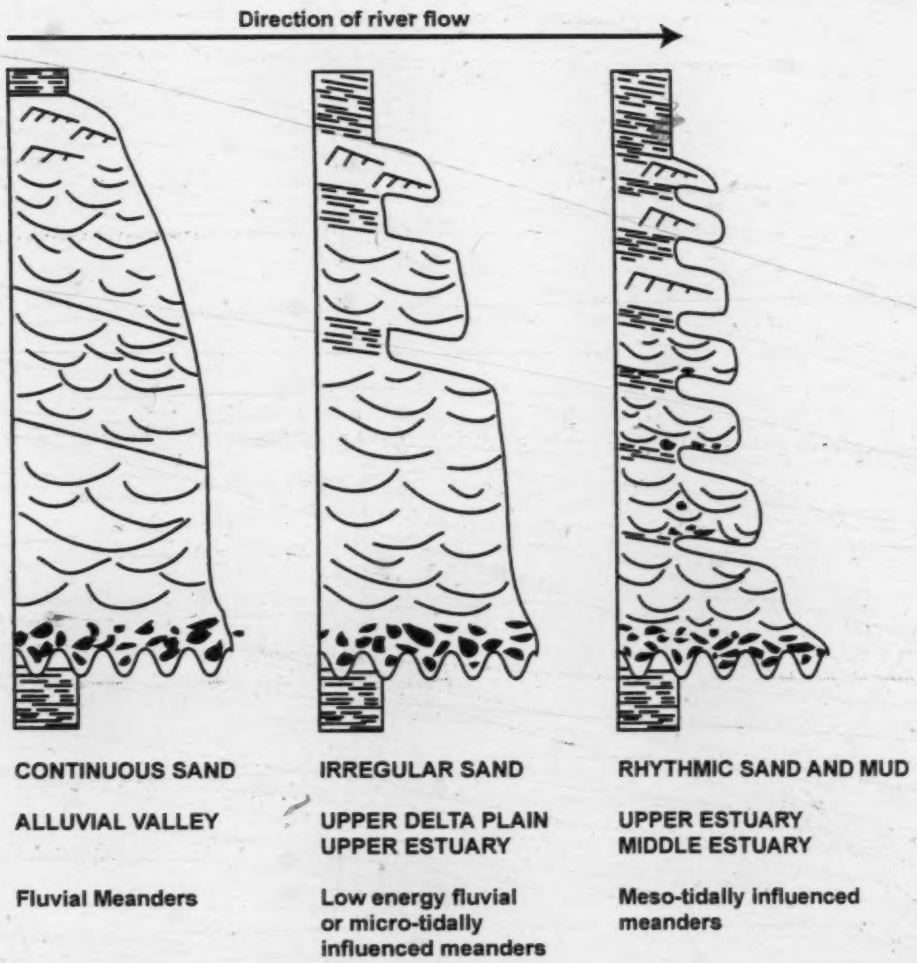


Fig. 2.35. Facies models of point bar morphology related to positions in an estuarine complex (Smith, 1987). Point bars in FA2 are most similar to a mix of the continous sand and irregular sand models (modified from Smith, 1987).

(F2c) and grey mud (F4a). Allen (1991) developed a classification of five textural profiles to characterize the fluvial to tidal transition of the Gironde Estuary. The two textural profiles seaward of the upper tidal limit correspond with the facies succession in FA2. This is similar to the comparisons with Smith (1987). Ancient and modern examples of tidally influenced IHS have been described that contain the same indicators and character as FA2 (Howard *et al.*, 1975; Clifton, 1983; Smith, 1987, 1988a; Thomas *et al.*, 1987; Rahmani,

1988; Lavigne, 1999, Gingras, 1999).

As Allen (1991) noted in the Gironde Estuary, tidal current reversals influenced fluvially dominated channels 50 kilometers upstream from the limit of salt intrusion. This suggests that although the sand and mud were not deposited in brackish waters, the fluvial system was influenced by the estuarine system. As the estuary is considered to extend from the seaward limit of coastal facies at its mouth to the landward limit of tidal facies at its head (Fairbridge, 1980; Dalrymple *et al.*, 1992), the tidally influenced sediments of FA2 are hereby referred to as estuarine and not as fluvial.

Two main features of an estuary that could contribute to the deposition of the fine-grained material of this facies association are the salt wedge and the turbidity maximum. The salt wedge is a term used to describe the hydrological stratification found within an estuary. This hydrological stratification occurs when denser saline water flows below less dense, fresh water with the boundary between the two expressed as an inclined surface facing landward (Postma, 1967; Dalrymple *et al.*, 1992). The development of a seaward thickening wedge of higher salinity bottom water (salt wedge) defines the estuary. This wedge is not a static feature. The salt wedge migrates upstream or downstream in response to tidal and fluvial discharge variations (Postma, 1967; Pritchard and Carter, 1971; Nichols and Biggs, 1985)(Fig. 2.31). This migration aids in creating an alternation in depositional setting that manifests as the seasonal change from the sand beds in F2b to the mud beds in F2c. It is proposed that Facies Association 2 represents deposition at the landward edge of the salt wedge at high tide.

Tidal current asymmetry (time-velocity asymmetry) and density currents (estuarine circulation) typically trap sediments within the turbidity maximum (Allen, 1991). The turbidity maximum is named and identified as the location at which the water column holds the most flocculated fine material in a turbid current. It is the time and strength discrepancy of daily tidal currents (time-velocity asymmetry) and estuarine circulation at the salt wedge that maintain the turbidity maximum. Estuarine circulation is the direct result of

density differences between marine and fresh water as saline water carries a higher dissolved solids content (Pritchard and Carter, 1971). Postma (1967) noted that due to density gradients, bottom-hugging marine water generates transport upstream, while the overlying fresh water continues to transport downstream. Increased suspended sediment is deposited when it is trapped due to the cyclic flow around the salt wedge caused by the opposing flow. Low river flow conditions also maintain the turbidity maximum due to tidal current asymmetry and the associated slack water lags which increase the time available for quiescent deposition (Postma, 1967; Allen, 1991). Deposition proximal to the salt wedge/turbidity maximum increases the thickness of mud beds although the sand grain size may not change. The turbidity maximum therefore affects the mud components of FA2.

Clay flocculation has also been argued as a mechanism contributing to the maintenance of the turbidity maximum, allowing compositions of smaller grains to form and settle out from suspension (Meade, 1972; Kranck, 1981; Pejrup, 1988; Eisma, 1993). It is possible that these small, non-aggregated grains would be carried out of the estuary if the turbidity maximum did not exist. Flocculation is a factor in the high percentage of clays observed in the muds of F2c.

The turbidity maximum is affected in size and position by variations in flow conditions. During episodes of low fluvial input, the turbidity maximum and its zone of increased mud deposition is displaced landward and extends further landward than the upstream edge of the salt wedge (Bechtel, 1996; Lavigne, 1999). During seasons of high fluvial input, the turbidity maximum is shifted seaward (Allen, 1991). This process explains the distinct variation between burrowed and unburrowed facies of similar lithology and physical structures. This is evident between the unburrowed F2a, F2b, F2c and the burrowed F2d, F2e, and F2f that exist inside and seaward of the upstream limit of the salt wedge. Burrowing rapidly decreases landward of the salt wedge due to the decreased salinity, and overall lack of freshwater burrowers. Most large trace making organisms are limited to the seaward portion of the wedge as they cannot survive in fresh water. The very rare diminutive

traces found in the upper portions of this association indicate a stronger presence of the salt wedge that allows the organisms to generate traces. During periods of low fluvial input, the turbidity maximum affects mud deposition landward of the salt wedge in waters too fresh for biogenic trace makers. Seasonal variation in mud deposition was noted by Boggs and Jones (1976), de Mowbray (1983), and Lavigne (1999).

Facies Association 2 likely represents the increasingly tidally influenced, fluvially dominated estuarine channel deposits that comprise the lower portion of the transgressive systems tract (TST) in this area. The channel sands regionally overly the sub-Cretaceous unconformity sequence boundary and occupy structural lows on the surface, overlying the FA1 sediments.

FACIES ASSOCIATION 3 (FA3)

Facies Association 3 is characterized by the mud dominated facies F4a, F4b, and F4c. This facies association gradationally overlies FA2 and locally gradationally overlies Facies Association 4 (FA4). Facies Association 3 is regionally scoured by FA4. The typical succession of facies in FA3 begins with F4a which is gradationally overlain and/or intercalated by F4b. Facies 4c typically caps this association when it is not scoured by FA4. Facies 4b and F4c also intercalate.

Previous studies assigned a fluvial interpretation to the combination of FA1, FA2, and FA3 sediments (Carrigy, 1971; Flach, 1984; Ranger, 1994; Yuill, 1995; Wightman and Pemberton, 1997). Rennie (1987), Yuill (1995), and Bechtel (1996) separated the muddy facies association for interpretation. Rennie (1987) used sedimentological and micropaleontological evidence to interpret a deltaic marsh environment. A wide variety of pollens within his interpreted overbank muds and mud drapes within the channel sediments indicate a fresh water input. The interpreted bay fill muds of Rennie (1987) contained species of algal material and dinoflagellates indicating marine conditions through occasional

influxes of seawater. As stated previously, Flach (1984) provided palynological evidence that indicates freshwater conditions with rare brackish water influences. It is important to note that Flach (1984) did not analyze muds in this study area.

The overall succession of FA3 indicates deposition within the flood basin of a fluvially-dominated environment (Fig. 2.34). Reineck and Singh (1980) subdivided the fluvial environment into three different sub-environments: channel deposits, bank deposits, and flood basin deposits. Facies Association 2 is representative of channel deposits and proximal bank deposits in this scheme. Grey mud (F4a) with its laminated mud containing rippled sand lenses represents distal bank deposits. It is also important to note that this facies also represents channel abandonment fill when associated with FA2. Facies 4b and 4c represent flood basin deposits. Flood basin deposits occur when the fluvial system anastomoses to create platforms subject to deposition from flooding and overbank episodes only (Leeder, 1999). The channel deposits of FA2 have been observed to actively crosscut each other, scavenging previous deposits due to lateral migration of the channel. Figure 2.28 shows that deposits of FA1 and FA2 are limited to the lows on the Devonian unconformity while the deposits of FA3 occur after the lows are breached, generating an expansive flood basin.

Flood basin deposits are found distal to the channel environment. Grey mud (F4a), white silty mud (F4b), and dark grey carbonaceous mud with coal (F4c) are present within this depositional environment (Fig. 2.34). Rooting is a common feature to these facies and decisively indicative of vegetated conditions. The muddy facies contain organic material that increases in abundance upwards in the section from organic detritus to bedded coals. The muds are interpreted to represent suspension deposition in standing bodies of water within the flood basin. Periodic flooding of the flood basin provides the coarse grains found in F4a and F4b muds. The white silty muds may represent pedogenesis within a humid environment (Blatt, 1982; Miall, 1996). Reducing conditions associated with this type of environment allow for the formation of sideritic and pyritic nodules. These conditions

also allow for the preservation of organic material. The high organic content of the dark muds reflects the distal position from the fluvial channel environment. Bedded coals are the result of preservation of marsh and peat swamp environments within portions of the flood basin protected from marine and fluvial floods under continuously rising ground water conditions (Reineck and Singh, 1980; Blatt, 1982). The preservation of marsh and peat swamp environments is an indicator of eustatic sea level rise associated with the deposition of the McMurray Formation as a whole. Rising sea levels may provide the increasing water levels necessary for swamp development and maintenance (Ainsworth, 1994). The thick (>5m) accumulations of FA3 material developed as a raised swamp environment. This raised environment would limit the influx of clastic sediment from infiltrating the peat deposits and downgrading those deposits to carbonaceous shales (McCabe, 1984). The lack of lateral migration in the channel environments has permitted the preservation of these flood basin deposits. Under normal lowstand or highstand conditions, channel sinuosity would be high, increasing the likelihood that channel migration would actively eliminate the flood basin deposits through erosion (Schumm, 1993). In a transgressive setting, channel sinuosity and cross-cutting decreases due to an increase in accommodation space, improving the preservation potential of these deposits laterally as they would not be actively eroded. Channels would preferentially aggrade rather than accrete, increasing the degree of preservation of these deposits. This decrease in sinuosity expressed by rivers in a rising base-level setting is common (Schumm, 1993). The deposits of FA3 were therefore interpreted to be deposited in a transgressive systems tract.

FACIES ASSOCIATION 4 (FA4)

Facies Association 4 is characterized by a fining-upwards profile similar to FA2. The facies of FA4 appear in a predictable order: F1a, F1b, F1c, F2d, F2e, F2f, and F4a. In a complete succession FA4 begins with a sharp erosive base overlain by a thin F1a granu-

lar grading sand. This facies grades rapidly upwards into grain-striped high-angle cross-stratified sand (F1b) and then into small-scale cross-stratified sand (F1c). These units are overlain by thick assemblages of sand-dominated, burrowed IHS (F2e) intercalated with bioturbated to unbioturbated mudstone breccias in inclined sand (F2d, F2a, respectively). These units are consistently overlain by mud-dominated, burrowed IHS (F2f) and capped by grey mud (F4a). Bioturbation is a significant component of this facies association as all facies with the exception of F1a have documented bioturbation at the outcrop exposures. The F2 facies are rare to well bioturbated as shown by many core examples. The succession can repeat vertically with both complete and incomplete successions being preserved. Incomplete successions contain F1c, F2e, and F2f in that respective order.

The arrangement of facies that comprise FA4 indicate deposition within a strongly brackish estuarine channel environment. The overall fining-upward successions, abundance of burrowing indicative of brackish conditions, tidal signatures, and the abundance of well-burrowed Inclined Heterolithic Stratification (IHS) suggest an brackish estuarine channel origin (Fig. 2.36). The sharp lower contact of FA4 represents fluvially dominated channel erosion during transgression as the result of lateral channel migration (Fig. 2.37). The lags and graded cross-beds of F1a suggest the initiation of deposition started with the coarsest material in the thalweg (Reineck and Singh, 1980). The high-angle cross-stratified sands of F1b result from the deposition of subtidal bars in the channel. These migrating bars show well-developed grain striping indicative of tidal influence in coarser-grained deposits, as well as back-flow/reverse-flow ripples representative of tidal conditions (Allen, 1980; de Boer *et al.*, 1989; Wightman and Pemberton, 1997). The small-scale cross-stratified sands (F1c) that commonly overly the F1b deposits represent lower energy flow conditions on the larger channel bedforms as well as deposition on point bar surfaces. The sand- (F2e) and mud-dominated (F2f) IHS sediments reflect deposition associated with tidally influenced point bars in high to moderate (F2e) or low (F2f) flow conditions. The mudstone breccia in inclined sand (F2a, F2d) was the result of the erosion of previous

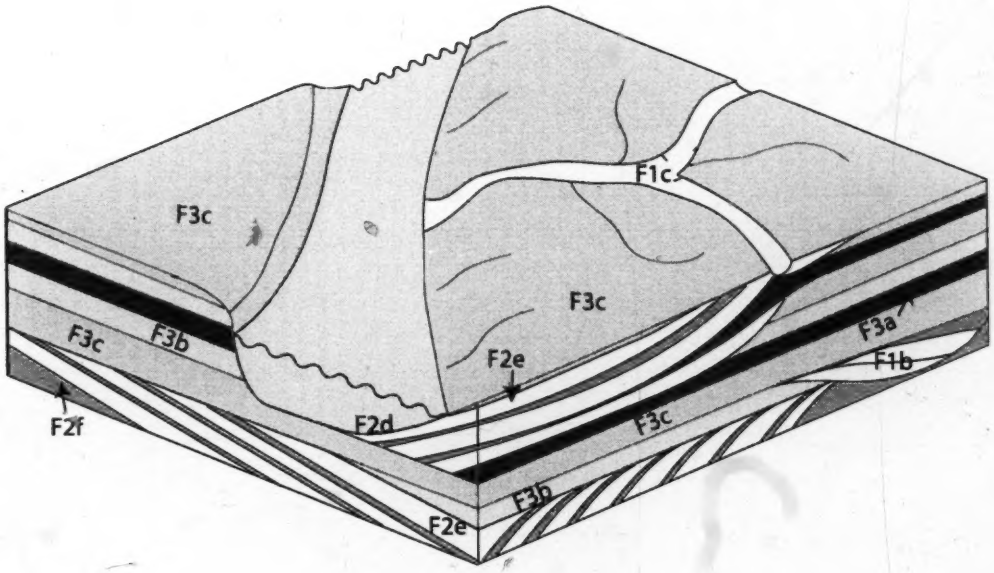


Fig. 2.36. Block model diagram of the depositional environment in which FA4 and FA5 were deposited. Large estuarine channels cut the tidal flats where small run-off channels deliver ebb tide water back into the larger channels. Facies Association 5 is deposited directly on the sediments of FA4.

point bar deposits and bank collapse into the channel thalweg. Examples of F2d containing the cylindrical clasts of *Cylindrichnus* rip-ups are sourced from point bar erosion associated with high-energy tidal conditions and short transport distances within the channel. The larger clasts are indicative of bank collapse on the outside of the meander loop. The grey mud deposition capping this sequence is interpreted as deposition from suspension in extremely low energy flow conditions indicative of decreased fluvial input.

Stratigraphically, the facies of FA4 occur in the middle of the McMurray Formation sedimentary column. Interpretation of the 'middle McMurray' channel successions is one of the most important issues in understanding the depositional history of the McMurray Formation. Previous work has identified several different interpretations for these sedi-

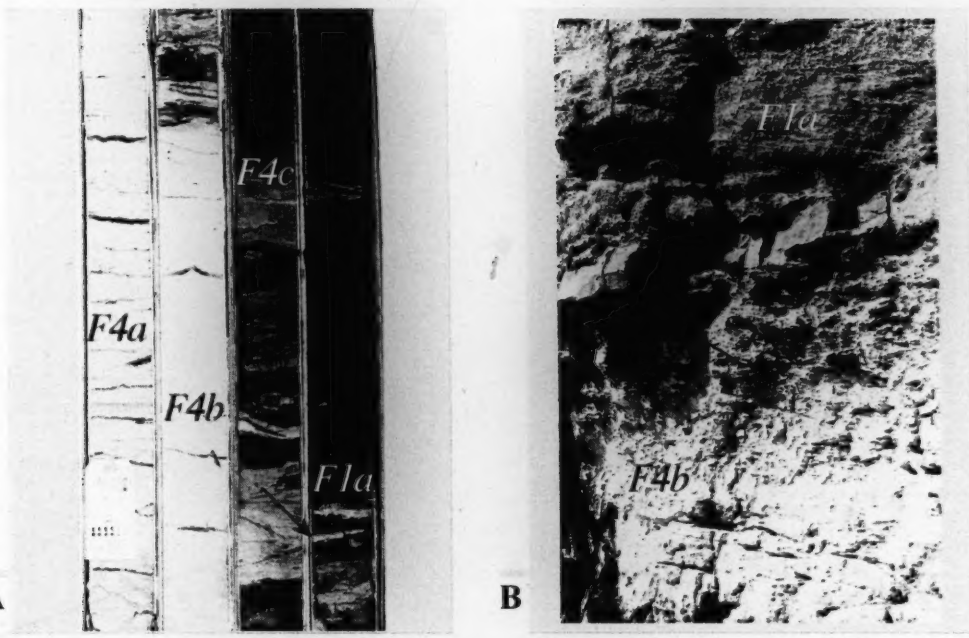


Fig. 2.37. A) This core shows a characteristic progression through the floodplain facies in FA3 and a sharp erosive contact with the overlying Facies 1a of FA4 (15-9-96-11W4). **B)** Outcrop A2 displays a sharp erosive contact between Facies 4b of FA3 and F1a of FA4 (A2).

ments. Flach (1984) and Flach and Mossop (1985) interpreted these deposits as fluvial with periodic marine incursions. Carrigy (1971) provided a deltaic interpretation that ultimately led to the estuarine interpretations (Stewart and MacCallum, 1978; Pemberton *et al.*, 1982; Wightman *et al.*, 1987; Smith, 1987; Fox, 1988; Ranger and Pemberton, 1992; Yuill, 1995; Bechtel, 1996; Wightman and Pemberton, 1997).

The lowermost facies of FA4 (F1a, F1b, F1c, F2d, F2e) were deposited in a subtidal environment (Fig. 2.36). Features of FA4 similar to criteria identified for subtidal deposits by Clifton (1983) include: 1) extensive lag deposits; 2) units of inclined strata (IHS) more than 2 meters thick; 3) laterally persistent thin mud layers (from outcrop evidence)(Fig. 2.38); and 4) medium to large-scale cross-bedding. Smith (1988a) interpreted tidal bundles from outcrop as evidence of subtidal channel deposition within the McMurray Formation. The fine-grained layers appear as double mud drapes in various facies. These layers are

comprised of mud and fine carbonaceous detritus.

Tidal influence is clearly evident in all facies associated with FA4 with the exception of the thin F1a facies. Ichnological evidence from F2d, F2e, and F2f indicate that the facies association was deposited in brackish water conditions. Trace fossils are more abundant and diverse than those found in the more fluvially influenced and less tidally imprinted FA2. Trace fossils found in FA4 include: *Planolites*, *Skolithos*, *Arenicolites*, *Cylindrichnus*, *Gyrolithes* Type I and Type II, and *Conichnus*. The small overall size, simple burrow morphology, low to moderate abundances, low diversity, and a combination of traces from both the *Skolithos* and *Cruziana* ichnofacies suggest a brackish water host environment (Pemberton *et al.*, 1982; Wightman *et al*, 1987; Beynon and Pemberton, 1992; Ranger and Pemberton, 1992; Ranger, 1994; Bechtel, 1996; Gingras *et al.*, 1998; 1999b). Flach (1984) noted that the intensity of bioturbation increased upwards in the outcrops of the McMurray Formation along the Steepbank River. Smith (1988a) observed this feature in his mesotidally influenced IHS successions. In this study, the facies association shows an increase in burrowing intensity upwards as well as a change from monospecific assemblages to more diverse populations.

The repetitive character of the facies associated with FA4 give the strongest evidence for tidal influence. Physical and chemical variations resulting from tidal fluctuations were significant influences on the deposition of FA4. Chemical variations, especially those represented by salinity changes, resulted in the development of synaeresis cracks and alternating burrowed and unburrowed zones over a thin interval in the same facies. Burrows by opportunistic organisms that are able to tolerate the variable physiological stresses associated with the estuarine environment evidence this. Physical variations in the estuarine environment are also reflected in the sedimentological and ichnological features of FA4. Sharp-based sands deposited in high-energy conditions grade into muds deposited during lower energy settings. Rhythmic deposition of sand and mud couplets is interpreted to be the dominant feature of these estuarine channels. Similar rhythmic deposition also occurs

in the flat-lying sediments expressed as sand laminae or silt laminae in F4a as well as the tidal flat deposits of FA5.

There are other features inherent to FA4 indicative of fluctuating energy conditions. The presence of angular mud rip-up clasts and ripped-up *Cylindrichnus* fragments are the result of short distance transport of eroded muds (Boggs, 1995), dewatered and desiccated or compacted during low water level conditions. Monospecific assemblages of trace fossils demonstrate colonization of a substrate by opportunistic organisms following an episodic depositional event or in an environment amenable to those organisms exclusively. The passively sand-infilled shafts of *Planolites*, *Arenicolites*, *Skolithos*, and *Cylindrichnus* within muddy intervals may represent exposure and dewatering of the muds prior to subsequent submergence and infill similar to the *Glossifungites* surfaces described by MacEachern *et al.* (1992) and Gingras *et al.* (1998b). Escape traces found in the sandy facies represent an organism's response to rapid sediment deposition.

Mud is also an important component of FA4. It is a distinctive feature of many of the facies comprising FA4 and its abundance is another characteristic that separates FA4 from FA2. Dalrymple *et al.* (1992) identified mud as a distinguishing feature of an estuary. Dorjes and Howard (1975) and Allen (1991) used mud to identify geomorphologic boundaries within an estuary (Fig. 2.30). As noted in FA2, Allen (1991) described the increased mud content of estuarine point bars downstream of the fluvial-tidal transition zone. The point bars described by Allen (1991) contain cross-bedded to rippled-laminated sand, with abundant flaser bedding and mud laminae similar to FA4. Mud content in an estuary can be attributed to the turbidity maximum around the salt wedge. The upper, increasingly muddier sediments of FA4 are deposited as a direct result of the turbidity maximum. This feature has been interpreted to represent continued transgression experienced during McMurray sedimentation. The location of the Facies Association 2 at the landward limit of the salt wedge/turbidity maximum (Fig. 2.31) compared to the location of Facies Association 4 inside and seaward of this limit provides for an increase in mud, tidal structures,

and bioturbation in FA4. The placement of mud-dominated sediments from the central part of the estuary over sand-dominated sediments typical of the inner reaches of the estuary represents transgression (Dalrymple, 1992). Ainsworth and Walker (1994) suggest changes in relative sea level to explain the relationships of sand-dominated and mud-dominated estuarine channels within the Cretaceous Bearpaw Formation-Horseshoe Canyon Formation transition.

The outcrop exposures of FA4 show mud layers draping entire point bar surfaces (Fig. 2.38). This was also noted for 'middle McMurray' sediments to which FA4 is analogous (Flach, 1984; Flach and Mossop, 1985). This is evidence for tidal influence in FA4 sediments. The high tide or high water conditions generate a bankfull stage with very low flow conditions during the post-flood slack water. Within fluvial systems, bankfull stage is achieved during high discharge periods where mud deposition is considered unlikely in the channel environment (Reineck and Singh, 1980). The long draping muds outlined in figure 2.38 display the draping nature at the outcrop level where a rather complete estuarine channel section is exposed.

Moderately- to well-burrowed, sand-dominated examples of FA4 reflect deposition between the inner and central zones of the estuary (Fig. 2.31). Increased bioturbation is a direct result of increased salinity in the water column (Bromley, 1990). The occurrence of mud interbeds marks the boundary between entirely fluvially dominated sedimentation and mixed fluvial-tidal sedimentation. In Smith's (1987) threefold lithofacies classification of point bars in different meandering river environments, the mesotidally-influenced deposits are distinctive due to their higher mud content (Fig. 2.35). They are therefore deposited within the upper to middle estuary. Mud content is increased in FA4 versus the similarly fining upwards association of FA2. This division based on mud content is not always so simplistic, rather an overall feature noted from several examples. Mesotidally influenced point bar facies are distinctive in that they contain IHS (Smith, 1987).

Mud-dominated, well-burrowed examples of FA4 reflect deposition in the central

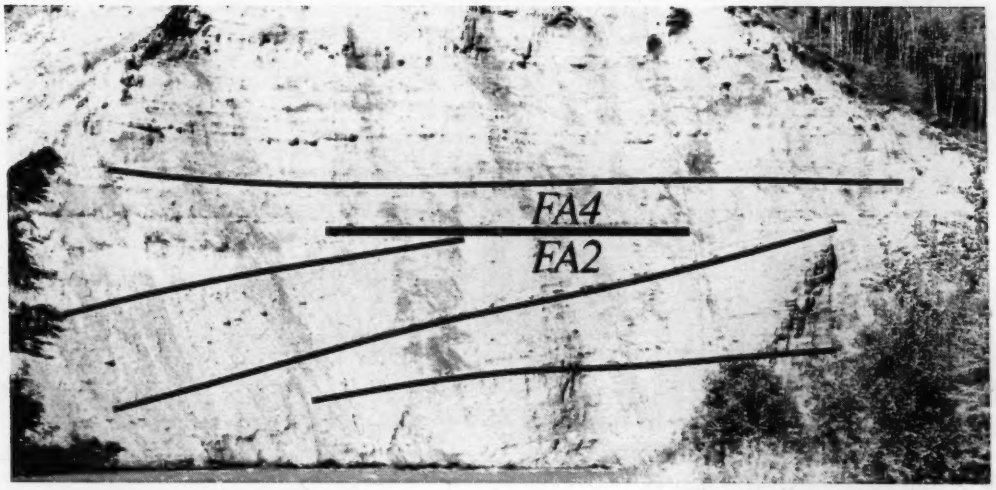


Fig. 2.38. Long draping muds are commonly observed in outcrop as shown in this example from E14. The draping muds of FA2 are identifiable as are the draping muds of FA4 dipping into the face. The erosional contact between the two at this location is shown in black.

(middle) zone of the estuary. High suspended-sediment concentrations coupled with the turbidity maximum of the estuary result in increased mud deposition. Mud deposition from the turbidity maximum in the central estuary is a direct result of density currents, tidal asymmetry, and clay flocculation (Eisma, 1993). Dorjes and Howard (1975) described middle estuarine facies as interbedded sand and mud with moderate bioturbation. The upper estuary at Willapa Bay described by Gingras *et al.*, (1999a) was characterized as interbedded silt and mud. The authors note that the lack of sand is mainly due to the fact that at Willapa Bay, the sediment input is dominantly through the inlet and not from fluvial sources. The dominant source of sediment during the McMurray Formation was from fluvial sources (Fox, 1988; Wightman and Pemberton, 1997). This is evidenced by the high (>95%) amount of angular to subangular grains derived from the Canadian Shield found upstream from the main depo-center.

Examples of FA4 represent sedimentation in a transgressive systems tract (TST).

This association is a result of an overall continuing transgression placing estuarine sediments above fluvial sediments in a vertical succession.

FACIES ASSOCIATION 5 (FA5)

Facies Association 5 is characterized by moderately to well-burrowed, flat-lying, interbedded, sand and mud. FA5 is composed of facies F1c, F3a, F3b, and F3c. This facies association is laterally extensive when present in thickness greater than one meter. These flat-lying sediments have been separated from the underlying FA4 inclined beds due to their horizontal nature (Fig. 2.36). In many outcrop exposures in this study FA5 marks the top of the exposed McMurray succession. Facies Association 5 commonly overlies FA4 however the two facies associations are known to intercalate in meter scale packages. The intercalation of these two facies associations results in a distinct inter-fingering relationship (Fig. 2.28). The upper contact between FA5 and FA6 successions is typically sharp, representing a scoured or eroded surface.

The constituent facies of FA5 do not occur in a predictable vertical order. The association is gradationally bound beginning with horizontally interbedded mud-dominated sand and mud with varying degrees of bioturbation (F3c) or mud and sand with bioturbation (F3b) at the base. The component facies conformably and gradationally overlie the FA4 material. The biogenically churned sediments of F3b may gradationally overly the F3c sediments and vice versa. The entire succession is commonly capped by the horizontally interbedded sand-dominated sediments of F3a that also contain variable bioturbation. All of the F3 facies inter-finger with each other. The F1c small-scale cross-stratified sand is seen in this association but is only documented from two outcrops and five cores. The occurrence of F1c in this association represents the basal material of tidal run-off channels in tidal flat environments capable of providing and sorting upper fine-grained sand. In outcrop examples, F3a gradationally overlies examples of FA4 containing low mud contents.

Core examples display consistent gradation of muddy associations of FA4 into F3c or F3b facies.

Facies Association 5 is interpreted to represent tidal flat deposits associated with inner to central estuary point bars. The flanking tidal flats interpreted here are not associated with the widespread coastal tidal flats described by Evans (1965) or Klein (1977). Fringing tidal flats have been described from the modern Solway Firth (de Mowbray, 1983), Willapa Bay (Clifton, 1983; Gingras, 1999a), Cobequid Bay (Dalrymple *et al.*, 1991), and the Gironde Estuary (Allen, 1991). The environment of tidal flat deposition is topographically higher than that for a point bar complex, and as such represents the vertically aggrading component of an estuarine channel complex. This explains the consistent gradational association of FA5 over the sediments of FA4 (estuarine channel).

This study attempts to differentiate sandy tidal flats, equal sand and mud flats, and muddy tidal flats based on the overall ratio of coarse to fine grains. This leads to the identification of sand flat, mud flat, and mixed flat facies. This is consistent with a number of early tidal flat facies models, notably those by Klein (1977) and Reineck and Singh (1980). Modern tidal flats are abundantly to pervasively bioturbated (Reineck, 1967; Frey and Basan, 1978; Clifton, 1983; Gingras, 1999). Characteristics suggesting depositional conditions of the three main tidal flat facies (F3a, F3b, and F3c) are shown in figure 2.39.

Sand-dominated flats (F3a) are characterized by the relatively coarse, well-sorted grain size of the sediment and paucity of burrowing over certain intervals. This paucity is due to flood conditions depositing and physically reworking the sand faster than the organisms can burrow. The low flow velocity subsequent to the flood conditions results in increased bioturbation and mud content. Reineck and Singh (1980) describe three conditions of waning flow energy on a tidal flat: 1) sediment laden flow becoming unconfined after leaving the channel onto the tidal flat, 2) a decrease in energy related to an episodic event such as flooding due to storm events or seasonal floods, and 3) waning energy related to the waning tidal energy associated with the cycle. The rare nature of these deposits sug-

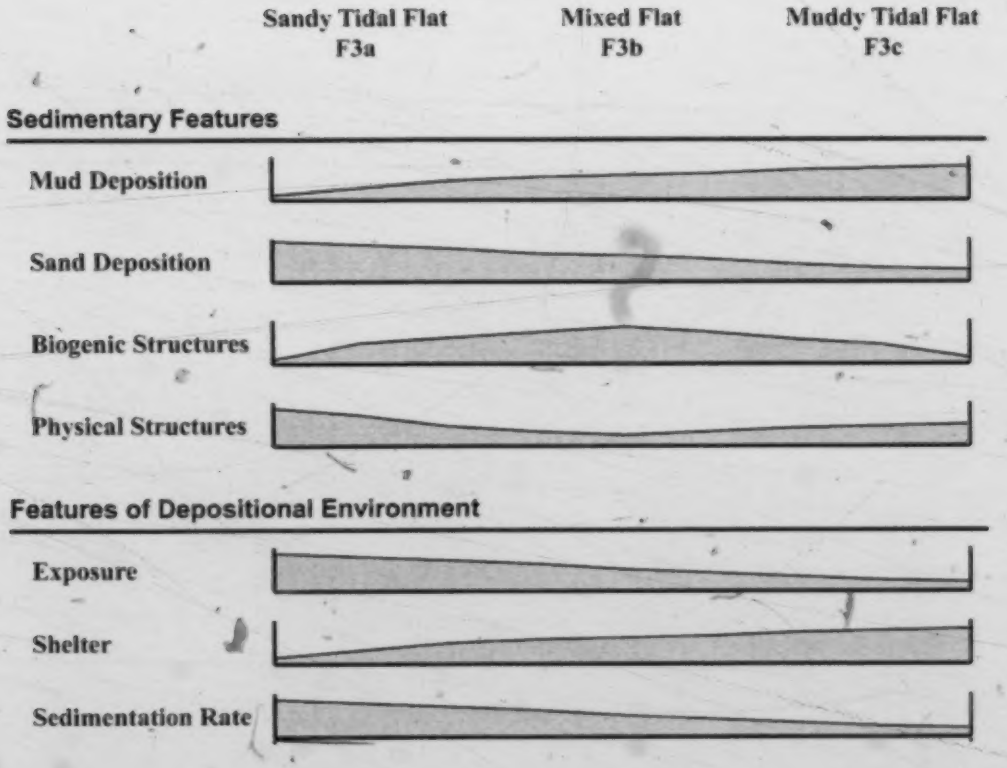


Fig. 2.39. Comparison of features and suggested environmental parameters for the tidal flat facies of FA5 (modified from Bechtel, 1996). Schematic relative values are shown and do not infer specific value relationships between the facies.

gests an episodic event rather than diurnal tidal processes or overbank flows, was responsible for this sedimentation pattern. Often these sediments occur in a significant interval of small-scale cross-stratified sand. This accumulation is identified as the sand flat expression of F1c. The small-scale ripples displaying asymmetry and combined flow character on these tidal flats indicate low energy flow related to unbalanced tides and shallow water where slack water conditions allow for the development of waves. Waves have the greatest effect near the high-tide level as fetch is the greatest (Yeo and Risk, 1979).

The gradational and unordered pattern in which the facies of FA5 appear is a direct expression of the physical and biological processes that occur on an intertidal flat

system. A predominance of flood tide and episodic depositional flooding events result in the sand-dominated facies with moderate bioturbation represented by F3a. The dominance of low-energy conditions on a shallow sheltered tidal flat is represented in F3c. This mud-dominated facies with moderate bioturbation indicates quiescent conditions on the tidal flat. Muddy tidal flat morphology and occurrence are dictated by the associated sand flats that occur in a more proximal position to the main channel thalweg. The erosion and deposition of mud flats is therefore the result of movement of the sand flat facies (Dalrymple *et al.*, 1991). Muddy flats of the Cobequid Bay in northern Nova Scotia are directly influenced by the axial sandy facies (Dalrymple *et al.*, 1990; 1991). Changes in the mud flat morphology are due to slight changes in the main channel orientation (Clifton, 1983) as channel migration develops terraces on the flanking tidal flats.

The biogenically churned sediments of F3b represent an environment amenable to biological organisms. The equal ratio of sand to mud in this environment allows burrowers preferential to sand and those preferential to mud to coexist in a protected moderate energy environment. This central facies in the equal mud/sand continuum is typically abundantly bioturbated by a low diversity assemblage of trace fossils. The equal relationship of sand and mud allows colonization of the substrate by organisms with an affinity to either or both. This relationship does preclude organisms unable to tolerate one of the substrates. There is a bias towards animals suited to both substrates. The churned fabric typically destroys all physical structures. This indicates that the flat facies are central in the estuary and the mixed flat facies of F3b is located in one of the most amenable environments in the estuary.

It is important to recognize that the same physical processes occur in each environment as observed by the sedimentary structures in the unbioturbated intervals of each facies indicating a geographic proximity. The relationship of mud to sand has created three independent facies comprising a grain-size domination continuum. Sand interbeds in a mud-dominated system undergo the same physical processes of deposition and reworking

as sand interbeds in a sand-dominated system, with the only difference being the overall dominating energy conditions.

The sediments of FA5 show a similar ichnological signature to the moderately to well-burrowed sediments of FA4. This brackish association of traces is common in the middle (central) estuary. Tidal flat deposits represent deposition on the upper plane of large point bar complexes associated with the main channel (Fig. 2.36). These deposits are found from the inner (upper) estuary to the middle (central) estuary (Fig. 2.31). The tidal range modifies the inter-channel highs into tidal flats due to tidal inundation. This is an environment dominated by tidal currents and waves and not by fluvial processes unlike the associations of FA1, FA2, and FA4 which have a significant fluvial influence on sedimentation. Deposition on the tidal flats is less affected by fluvial processes with the exception being tidal run-off channels that cross the tidal flat (Fig. 2.36). These run-off channels are expressed as sand and mud and can appear burrowed. The fining successions of minor inclination noted in the study area (F1c to F3c) represent the preservation of these channels.

Facies Association 5 represents sedimentation in a transgressive systems tract (TST). This association is a result of an overall continuing transgression placing and preserving tidal flat deposits over central estuary channel deposits (FA4) in erosional contact with the fluvial flood basin sediments of FA3.

TIDAL RAVINEMENT SURFACE (TR 1)

The sharp, commonly erosional contact between FA5 and FA6 is a significant stratigraphic surface that separates central estuary sediments from outer estuary sediments. It is termed a tidal ravinement surface (TR 1)(Fig. 2.28). Several sedimentologic changes occur across this surface and it represents one of the most significant and sharp divisions in sediment character in the McMurray Formation (Fig. 2.40).

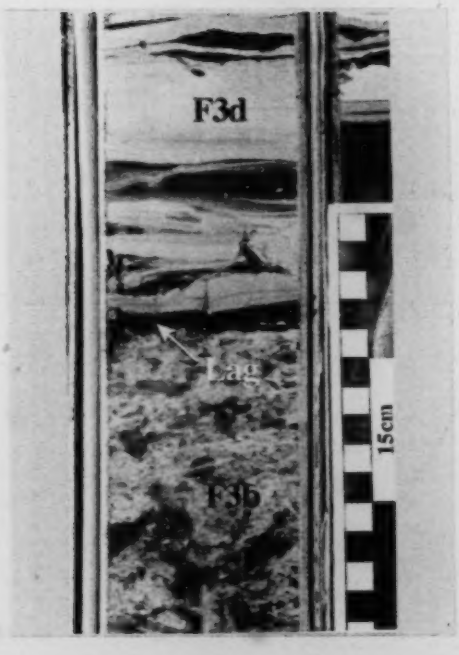


Fig. 2.40. Tidal Ravinement Surface (TR1). This surface separates inner estuary sediments from outer estuary sediments in a transgressive setting. In this example, the surface displays a coarse sand lag above an erosional contact. The surface is marked in red.

Allen and Posamentier (1994) first defined a similar surface in work completed on the Gironde estuary in France. Stratigraphic sections of sediment from the Gironde estuary indicated tidal channel, estuary mouth, and flood tidal delta sand were separated from fluvially dominated sediments of the inner and central estuary. Bechtel (1996) also identified this surface in the McMurray Formation southeast of the study area. This is an irregular surface that can incise deeply into the underlying sediment and is not expected to be isochronologically significant. It is indicative of continued transgression. The Gironde tidal ravinement surface commonly contained a gravel lag not observed in this study.

FACIES ASSOCIATION 6 (FA6)

The FA6 facies association comprises F1d, F3d, and F3e. This facies association is interpreted as central bay fill to barrier bar/shoreface sediments. The mud contained within this facies association is a darker color mud than found in facies associations previously described. The darker mud of FA6 is also less waxy and more fissile than the muds associ-

ated with FA1-FA5. Facies Association 6 also contains more robust trace fossils in greater diversities than those previously identified in other facies associations. This facies association is rarely observed in outcrop sections due to recent erosion related to the modern Ells River valley development. This facies association is based primarily from core data surrounding the Ells River outcrops. Two outcrops, E13 and E16, show the base of F3d but are glacially scoured and therefore do not display a complete succession through to the Wabiskaw in the central Ells River study area. Outcrops containing the Wabiskaw member of the Clearwater Formation do occur along the Ells River but in areas of poor overall exposure upriver that were not described for this study. This facies association represents the uppermost sediments of the McMurray Formation in this area. The Wabiskaw is only observed in core in the central Ells River study area.

The individual facies sharply overlie each other with very little internal scouring. The three facies comprising this association can inter-finger with each other although F3e commonly precedes F3d in a vertical succession. The facies of FA6 are compared using depositional factors such as salinity and water current energy in figure 2.41. The lower contact of FA6 is typically sharp to scoured in core and outcrop exposure. Petrophysical logs of successions interpreted to represent FA6 commonly show a sandying upward profile on the gamma ray log. The stratigraphic succession of facies in these coarsening upward profiles is commonly F3e, F3d, and possibly F1d if it is present. The facies exhibit grain size increases internally upwards, particularly the F3d facies. Successions that grade upwards into F1d show a stronger affinity to a sandying upward profile on the gamma ray log (Fig. 2.42). This succession is seen only in core as insufficient section exists at outcrop exposures.

The facies of FA6 all share several distinct characteristics. The angle of bedding in FA6 facies is predominantly horizontal with very slight, if any, inclination. The sediments are laminated with sand, silt, and mud and commonly appear bioturbated. The ichnological characteristics of these facies separate this association from other facies associations. The

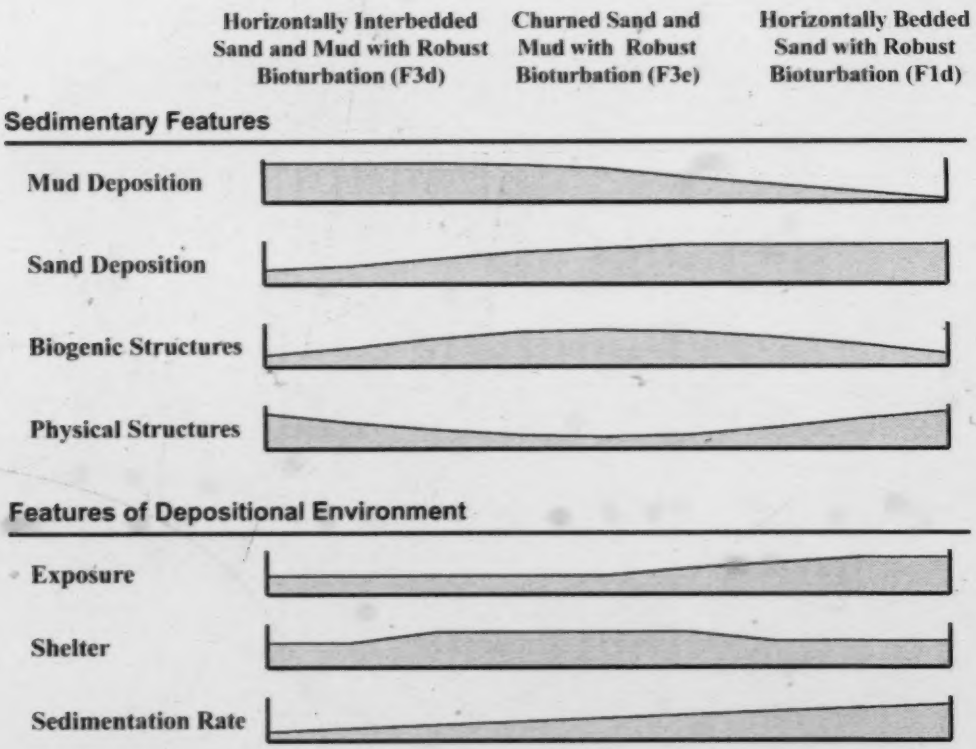


Fig. 2.41. Comparison of the features and the suggested environmetal parameters that affect them for the facies found in FA6. The bars suggest a relative increase or decrease in the parameter of feature relative to the other facies and do not infer a specific value.

trace fossils present in FA6 facies are robust, highly diverse burrows displaying complex morphology. This suite of traces most likely comprises an equilibrium population due to these features. An equilibrium population composed of complex burrows require a significant time period to build and expand to the point of generating a moderate to high intensity bioturbation fabric (Buck, 1987; Pollard *et al.*, 1993). Opportunistic suites exist in F1d but are cross-cut by the later equilibrium population, which establishes an ecological balance. These larger and more complex burrows are made by organisms less tolerant of salinity fluctuations in the water column. These organisms create burrows displaying a complex morphology relative to the simple morphology of the opportunistic burrows

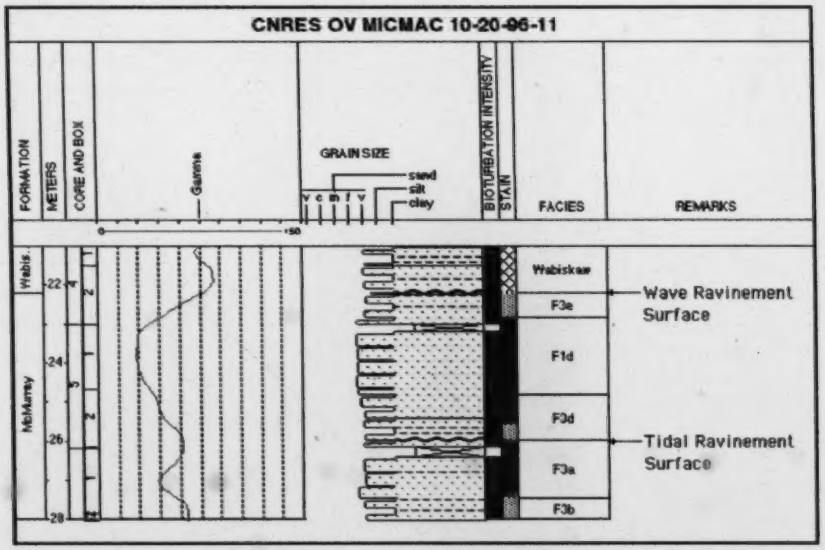


Fig. 2.42. Coarsening upwards profile seen in the core grain-size profile and the gamma ray electric log. The facies relationships at the top of the McMurray Formation here are evident and display the packaging of Facies Association 6 between the Tidal Ravinement Surface and the Wave Ravinement Surface.

found in FA1-FA5. The burrows of FA6 represent a distinct assemblage not present in other facies associations.

Facies Association 6 is present in other areas of the Athabasca Oil Sands deposit. The marine nature of the physical and biogenic structures differentiate these sediments from the underlying estuarine and brackish sediments. This marine unit was first observed by Carrigy (1963a) who noted similarities with the Wabiskaw member. Carrigy (1963a) noted the scoured nature of the lower bounding contact and identified the radical change that occurred across it. Jackson (1984), Cuddy and Muwais (1987), and Bechtel (1996) all noted a similar marine unit in the upper portion of the McMurray that displayed a scoured base but did not contain the glauconite that marked the base of the Wabiskaw member. This author agrees with the above researchers in placing the Wabiskaw member at the first appearance of glauconite and identifying and classifying the McMurray marine unit independently. This unit is not the middle McMurray "marine unit" identified by Fox (1988)

due to the significant differences in sedimentary character between the unit of Fox (1988) and the unit identified by Carrigy (1963a) and this study. Due to the strict definition of Badgely (1952), this facies association is grouped with the McMurray sediments rather than with the Wabiskaw member per Wightman *et al.* (1997) and Hein *et al.* (2000).

The facies in FA6 represent deposition in the outer regions of the estuary. Facies 3d is characterized as interbedded sand and mud with robust bioturbation. This facies was deposited in a somewhat sheltered area of moderate salinity and sedimentation rates with rhythmic deposition of sand and mud (Fig. 2.43). Facies 3e was deposited in a sheltered area with low sedimentation rates in a rhythmic pattern. The salinity levels associated with the water column in the area of deposition of F3e were quite amenable to trace fossils as seen by the abundant bioturbation. Interbedded sand and mud in equal proportions constitutes the most abundant facies within the modern outer estuaries of Georgia (Howard and Frey, 1973). Visher and Howard (1974) reported that mud and silt deposition occurred within shoal areas sheltered from ocean waves and strong currents within the modern Altamaha estuary in Georgia. The quiescent bay reported by Gingras *et al.* (1999a) in Willapa Bay, Washington also shows an area of mud and silt deposition with sedimentary structures akin to those observed in FA6.

Facies 1d was deposited in an area of low mud deposition due to storm or event sedimentation (Fig. 2.43). The lack of diminutive bioturbation throughout this facies reflects the unsheltered environment of deposition of F1d where episodic high sedimentation and physical reworking rates prohibited complete colonization and reworking by organisms. The sediments of F1d also show an opportunistic suite of trace fossils colonizing the substrate before an equilibrium population becomes established and further reworks the sediment. This is evidenced by the cross cutting of the rare diminutive, low diversity suite by the more robust and diverse traces of the equilibrium population.

It is interpreted that the three facies comprising FA6 represent laterally adjacent environments of deposition in the outer estuary. F3d represents a central bay fill in areas

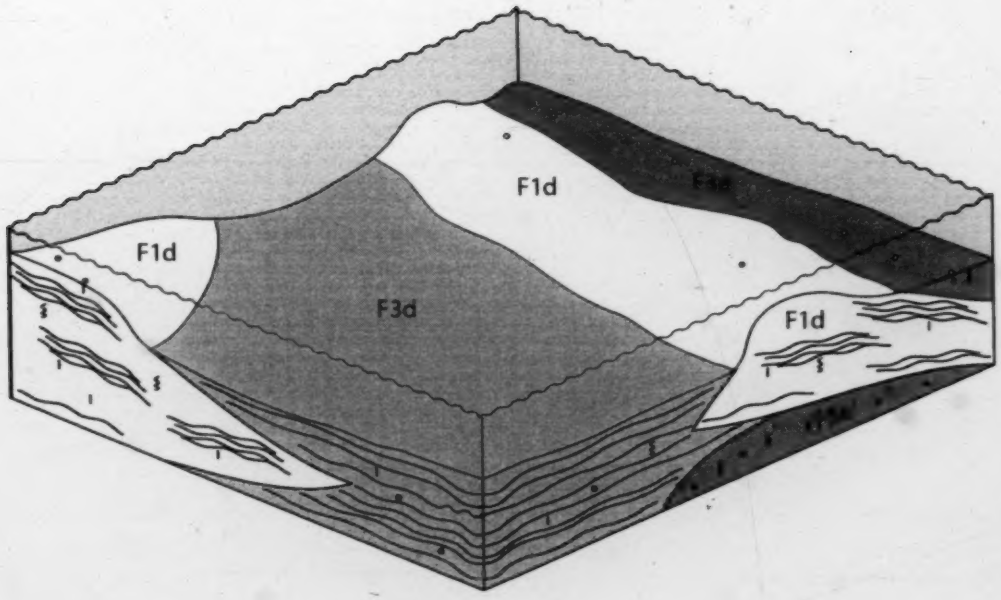


Fig. 2.43. Block model diagram of the suggested depositional environment for Facies Association 6. All facies are deposited subtidally in a bay environment and as such are not exposed above mean water-line. With few sharp boundaries, the facies commonly interfinger.

of increased and episodic reworking from tidal and wave energy. Facies 3e was deposited in a similar environment but protected from high sedimentation rates and reworking by sand bars or sand bodies (Fig. 2.43). Facies 1d represents subtidal bar deposits, flood delta deposits at the mouth of the estuary, or washover sands behind inter- to supra-tidal bars. The potential environments of deposition for F1d include rapid and short-lived episodes of sedimentation followed by prolonged episodes of lower sedimentation rates. Salinity levels in the facies of FA6 became high enough that many new organisms could tolerate the water chemistry.

The facies of FA6 represent outer or lower estuary deposits. The main energy influences have changed from fluvial and tidal to wave and tidal. This is displayed by the lack

of inclination expressed by fluvially influenced sediments and a predomination of wave produced sedimentary structures versus fluvially generated sedimentary structures.

WAVE RAVINEMENT SURFACE (WR 1)

The upper surface of the McMurray Formation is regionally scoured with low relief. This surface is planar and traceable not only through the study area, but throughout most of the McMurray Formation. This surface developed as a result of continued wave erosion associated with shoreline regression (Fig. 2.44). This transgressive surface of erosion (TSE) may also be defined as a high energy flooding surface (HE FS), which is a low-relief erosional surface across which no noticeable change in water depth is experienced (Pemberton and MacEachern, 1995). The expansive area equally cut by wave erosion is far more extensive and planar than the high-relief tidal ravinement surface identified between FA5 and FA6 (Fig. 2.28). This contact is a boundary separating estuarine sediments from fully marine sediments above (Fig. 2.28; 2.44).

This surface is equivalent to the wave ravinement surface described by Allen and Posamentier (1994). In the Gironde estuary this surface also separates estuarine bay fill from shoreface sands and muds. This surface was identified in the McMurray Formation by Bechtel (1996) southeast of this study but was divided into two similar surfaces that amalgamated seaward. Zaitlin *et al.* (1994) suggested that wave ravinement surfaces were not developed in exclusively tide-dominated estuaries. The presence of this surface indicates that the upper portions of the McMurray Formation (FA6) were not simply tide-dominated. This agrees with the interpretation of Facies Association 6 where wave influence equals or exceeds tidal influence. Wave ravinement surfaces were defined by Zaitlin *et al.* (1994) as regional, planar surfaces of erosion commonly overlain by fining-upward transgressive sequences incorporating retrogradationally stacked parasequences. Ranger (1994) described the Wabiskaw in this area to be of this character.

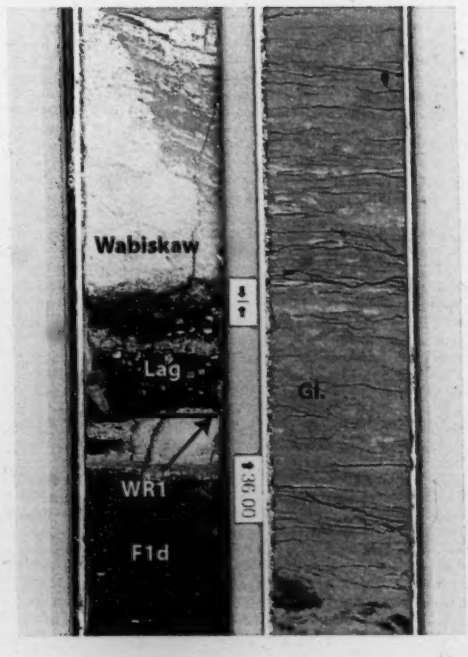


Fig. 2.44. Wave Ravinement Surface (WR1). This surface separates outer estuary sediments from shoreface /fully marine sediments in a transgressive setting. In this example, the surface displays a coarse sand lag above an erosional contact. Glauconite found abundantly in the overlying Wabiskaw member can be seen readily. The surface is marked in red.

CONCLUSIONS

The McMurray Formation sediments observed in outcrop and core in the vicinity of the Ells River in northeast Alberta display facies and facies associations consistent with an estuary developed in a lowstand to transgressive setting. From this data set, the lowermost facies association of FA1 occurs in lows along the sub-Cretaceous unconformity, and is interpreted as sediments deposited in a braided to meandering fluvial system during a local lowstand. The unconformity surface between the Devonian sediments and FA1 is a sequence boundary. The sedimentary structures and ichnologic signature of FA2 indicate that these sediments were deposited in a tidally influenced meandering channel succession landward of the upstream limit of the salt wedge and turbidity maximum. These sediments represent the basal accumulations in a transgressive systems tract. The muddy and organic facies found in FA3 are interpreted as flood basin deposits, developing paleosols and peat swamps distal to the tidally influenced meandering channels of FA2.

The incision of the coarse-grained F1a into the sediments of FA3 represents lat-

eral migration of channel bases and is an autocyclic feature of channel development in an estuary. The overlying FA4 facies display a tidal imprint with abundant brackish ichnological signatures suggesting an upper to central estuary channel complex. This meandering channel system was deposited as another expression of a transgressive systems tract. The overlying tidal flat facies association (FA5) is the topographic expression of inter-channel sedimentation in the central estuary. The tidal flat sediments are indicative of continued transgression where wave produced sedimentary features take the place of the fluvially produced structures. The outer estuary material of FA6 is defined by tidal and wave generated structures and a change from brackish trace fossils to more marine fossils of higher diversity. The sediments of FA6 are separated from FA5 by a tidal ravinement surface (TR 1). The wave ravinement surface above the FA6 separating the Wabiskaw Member of the Clearwater Formation from the McMurray Formation marks the end of McMurray deposition and continued transgression in a larger overall sequence.

Ichnology has proven a very effective aid in determining the sedimentary environments of each facies and linking the facies associations. The sedimentary structures in Facies Association 1 indicate a braided to meandering channel environment. The ichnofossil signature, or lack thereof, supports this interpretation. The rare brackish trace fossils and abundant tidal signatures combined with the inherent sedimentary structures of the facies in FA2 support a tidally influenced meandering channel environment. The transition to more common traces in examples of this facies indicate that this environment was typically landward of the salt wedge but that salinity was increasing up-section imprinting a stressed assemblage of brackish traces. The diminutive and monospecific traces found in the facies of FA3 are combined with the sedimentary structures of these facies to determine a flood basin depositional environment for this facies association.

The common trace fossils in limited and monospecific assemblages of diminutive marine forms found in the facies of FA4 aid in determining a central estuary environment for these sediments. The traces typically increased in size and abundance upwards indicat-

ing conditions were becoming less stressed throughout deposition of this unit. It is the ichnological signature that aids in separating the more estuarine meandering channels of FA4 from the mainly tidally imprinted sediments of FA2 that display no bioturbation. The facies that comprise FA5 are interpreted as tidal flat deposits due to the abundance of bioturbation in the flat-lying wave and tidally reworked sediments. The ichnological signature is very similar to that found in FA4 and hence these environments can be linked together as meandering, laterally-accreting central estuary channels (FA4) and their intrinsically related, topographically higher, vertically aggrading tidal flats (FA5). The facies of FA6 that sharply overly the FA4 and FA5 sediments display a very different ichnofossil assemblage than any facies previously observed. The trace fossils in the facies of FA6 are more robust and complex with a higher diversity of traces. This ichnofossil assemblage indicates a less stressed environment than indicated in other facies associations. When combined with sedimentary structures in the FA6 facies, they promote the interpretation of a more marine depositional environment such as the outer estuary where conditions were more amenable to a wider variety of burrowing organisms, and tide and wave produced structures dominated over fluvially produced sedimentary structures.

The identification of stressed-brackish and more marine influenced signatures has greatly influenced the delineation of facies associations and depositional environments. Ichnological and sedimentological analysis of the outcrops and core in the vicinity of the Ells River promoted facies divisions and associations that lead to a local genetic stratigraphic interpretation of the depositional environments. From the data and interpretations, a major transgressive system can be defined.

These depositional environments indicated that the McMurray Formation was deposited as a complete estuary sequence from fluvial through open bay settings. These depositional environments help to trace the transgression of the McMurray Sub-basin. This genetic stratigraphic interpretation compartmentalizes the sediments of the McMurray Formation in this area and provides a predictive tool for characterizing the strata.

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CHAPTER 3 - OUTCROP-SCALE UNDULATION AND HETEROGENEITY OF AN IMMOBILISED BITUMEN-WATER CONTACT, MCMURRAY FORMATION, NORTHEAST ALBERTA

INTRODUCTION

The Athabasca Oil Sands deposit is located in northeastern Alberta and is one of four major oil sands deposits in Alberta. The other three are the Peace River, Wabiskaw, and Cold Lake deposits (Fig. 3.1). The Athabasca Oil Sands deposit is one of the largest hydrocarbon accumulations in the world with the bulk of the reserves contained in the Lower Cretaceous McMurray Formation. The best reservoir sands typically occur in the middle to lower part of the McMurray Formation and are commonly directly underlain by a basal water leg (Gallup, 1974; Mossop, 1980; Ranger, 1994). Because these are the most economically attractive zones, characterized by the thickest bitumen reserves, the nature of the bitumen-water contact can have significant consequences.

The McMurray Formation lies directly on the sub-Cretaceous unconformity, which, in the study area, is an angular unconformity exposing middle Devonian carbonate rocks at subcrop (Carrigy and Zamora, 1960; Andersen *et al.*, 1993; Ranger, 1994) (Fig. 3.2). McMurray sediments were deposited in fluvial, estuarine, and shoreface environments in a complex system of channel incision, valley fill and partially eroded shoreface systems (Pemberton *et al.*, 1982; Ranger and Pemberton, 1992, 1997; Wightman and Pemberton, 1997).

The basal bitumen-water contact of the Athabasca Oil Sands Deposit exhibits marked relief at many scales of observation. In outcrop the contact is prominent due to the contrast of the bitumen-saturated versus the water-saturated sands. The field area for this study (Fig 3.3) consists of the well-documented outcrops along the Steepbank River (Flach, 1984).

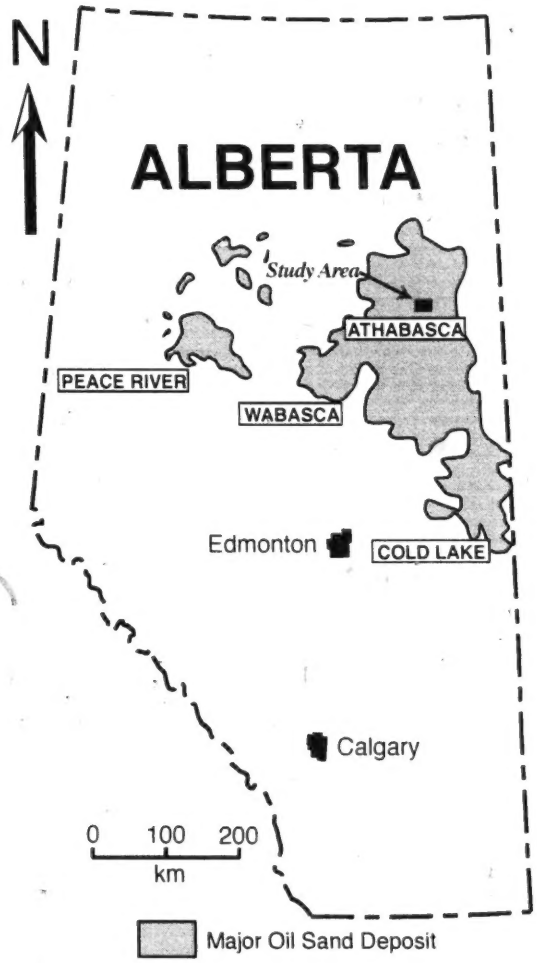


Fig. 3.1. The location of the four major oil sand deposits of Alberta. The study area is marked in the Athabasca Oil Sands deposit, the largest of the four.

At these outcrops, the bitumen-water contact exhibits as much as five meters of relief over a horizontal distance of just forty meters. The contact itself is heterogeneous, and is commonly characterized by isolated pockets of bitumen in the water-saturated zone as well as water pockets in the bitumen-saturated zone.

The primary focus of this study is to measure the variation inherent to the basal bitumen-water contact of the Athabasca Deposit and to conceptually apply these observations to the subsurface.

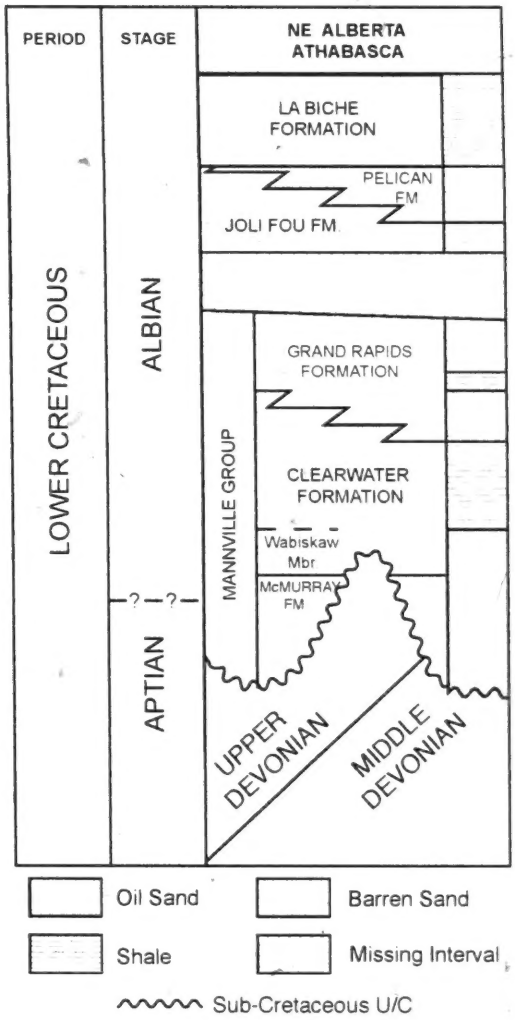


Fig. 3.2. The Lower Cretaceous Stratigraphy in the Athabasca area of northeast Alberta. The McMurray Formation rests immediately on the sub-Cretaceous unconformity.

GEOLOGY

The earliest and therefore lowermost sediments of the McMurray Formation are deposited from a fluvial depositional system (Carrigy, 1959; Flach and Mossop, 1985). Graded bedding and large scale cross-stratified sands dominate the sedimentary character of the early sediments. The middle section of the McMurray Formation at the Steepbank River outcrops has been interpreted as estuarine in origin. This is based on interpretations derived from observations of both physical bedforms and ichnofossils (Pemberton *et al.*,

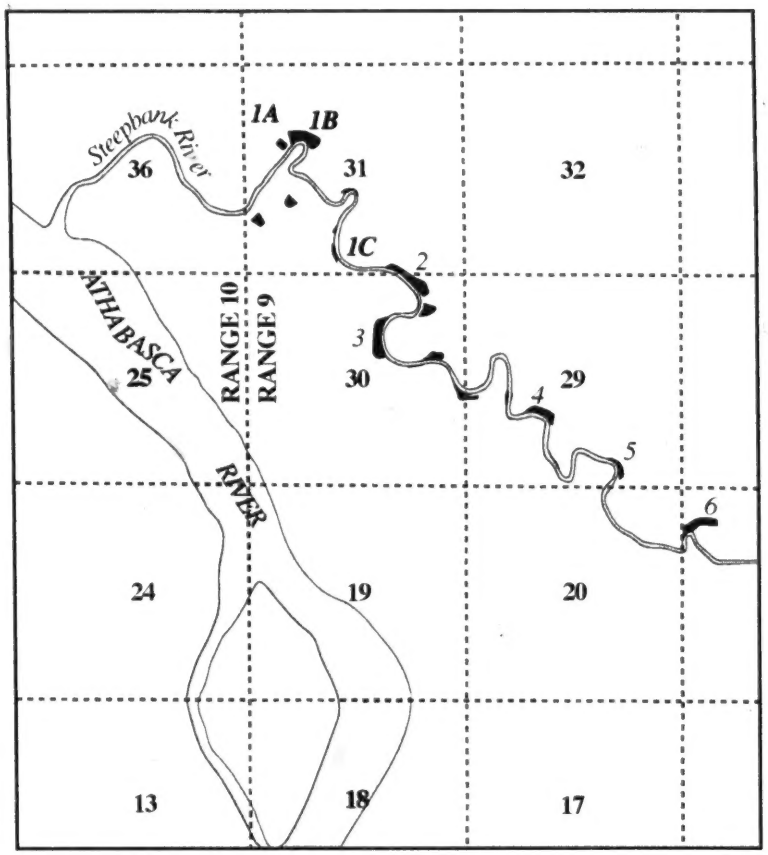


Fig. 3.3. The locations of outcrop exposures along the Steepbank River (Twp. 92, Range 9). The outcrops examined in this study are marked 1A, 1B, and 1C.

1982). This interpretation is further reinforced by the abundance of bioturbated inclined heterolithic stratification, which is commonly interpreted to represent preserved, laterally accreted, estuarine point bars (Howard *et al.*, 1975; Frey and Howard, 1986; Thomas *et al.*, 1987; Smith, 1988).

The upper sediments of the McMurray Formation are dominated by two depositional systems: a brackish estuary and a stacked brackish shoreface succession (Ranger, 1994; Ranger and Pemberton, 1997). Both of these systems represent continued transgression during Albian time. The stacked brackish shoreface successions can be observed in the

southern portion of the deposit, but are more poorly preserved toward the north (Ranger, 1994; Ranger and Pemberton, 1997; Caplin and Ranger, 2001).

METHODS

Tools for measuring precise position both laterally and vertically (e.g. GPS, barometric altimeter with base stations) are complex, expensive, and may not be easily portable. Furthermore, they do not have the centimeter to decimeter resolution desired for this study. Sight surveying equipment can also be error-prone, where error increases with greater distances. It is also difficult to generate a datum with a sighting system.

Hydrostatic levels using plastic tubing are designed for creating a datum for home construction and renovation. They are inexpensive and commonly available (Fig. 3.4). These instruments are based on the hydraulic principle that fluids maintain an equal elevation head when exposed to equal pressure at both ends of an open tube. One of the great advantages of this device is that it allows for working around corners and in difficult locations without a direct line of sight between two stations. The system is rated to have a vertical error of no more than 1cm per 20 meters of tubing length (verified by the authors). When using any reasonable length of tubing, the distance between stations does not influence the precision of the measurement. The hydrostatic level is therefore capable of measuring non-linear, non-equidistant, data points. The system only requires a single operator because the hydrostatic level is equipped with a sensor module attached to one end of the tube, which is fixed at the datum point and emits an audio signal when the fluid level is aligned with the datum point. Clear tubing was filled with red-dyed water to facilitate observation and measurement. At the Steepbank River outcrops, 30 meters of tubing were used which required about 600 ml of water to fill.

Due to the steep nature of the outcrop exposures along the Steepbank River, most of the data collection was carried out using climbing ropes and equipment. A datum eleva-

tion was established by measuring vertically from the surface of the river to the initial observation point on the bitumen-water contact at one end of an outcrop. The alarmed end of the tube (hitherto referred to as the fixed point) was positioned at the established datum point (Fig. 3.4). Stations were established by measuring the horizontal distance between the fixed point and successive points along the contact using a tape measure; then the vertical elevation change was measured. In operation, the free end of the tubing was raised or lowered until the water tripped the sensor module alarm mounted at the fixed point. At this point, the free end water level was level with the fixed end datum (Fig. 3.4). The datum level was marked on the outcrop and the vertical difference between the datum and the bitumen-water contact at that station could then be measured and recorded. Detailed grain size profiles were generated in vertical section at various points along the measured outcrops to quantify the local sedimentary character.

OBSERVATIONS

The oil-water contact is easily observed in outcrop due to differential weathering between the cohesive bitumen-saturated sands, and the less competent water-saturated sand. Furthermore, siderite cement gives the water-saturated sands an orange hue, whereas the bitumen saturated sands are dark gray. The contact may be sharp to gradational (5 to 20 centimeters in thickness) (Fig. 3.5).

The bitumen-water contact in the study area occurs in channel fill deposits. These deposits consist of high angle foresets of coarse-fine sand couplets and sand-dominated inclined heterolithic stratification (IHS) beds, interpreted to be the preserved remnants of tidally influenced, fluvial to estuarine bars and lateral accretion point bars. The bitumen-water contact is unperturbed where it intersects bedding planes and facies contacts separating the same lithology. In one location, the contact passes through a sharp boundary between high-angle cross-stratified sands and sand-dominated IHS sediments with no devi-

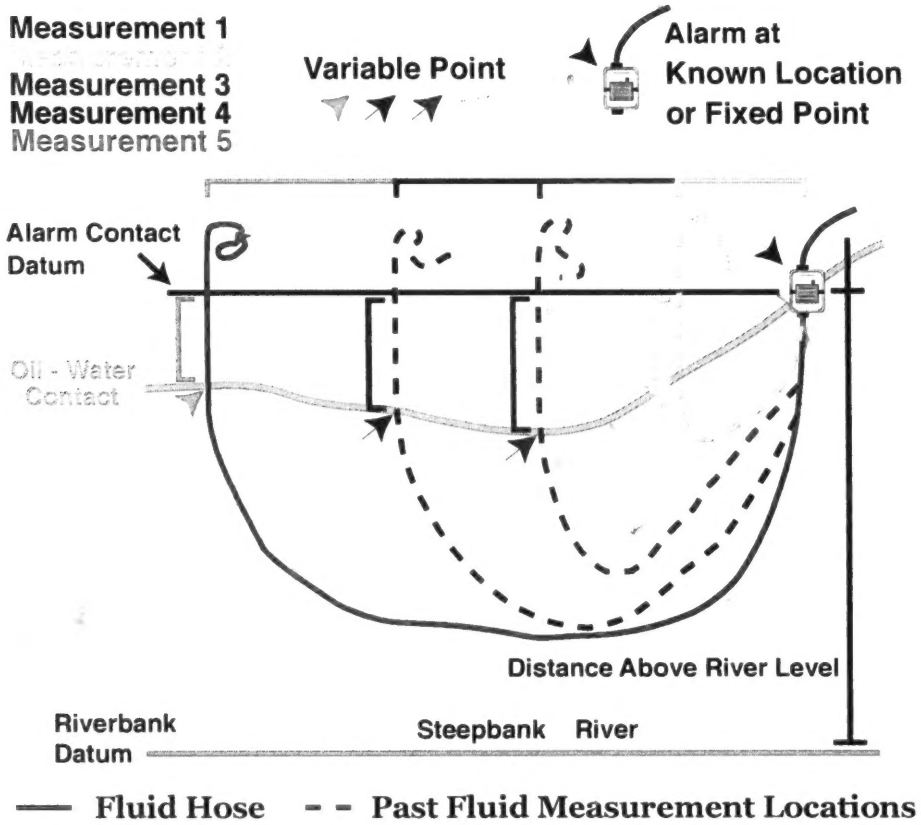


Fig. 3.4. Schematic diagram of the measurement apparatus and the technique used to obtain reliable horizontal and vertical measurements along the uneven surface of the outcrop exposure.

ation. Only surfaces separating different lithologies and grain sizes appear to affect the position of the contact.

The measured outcrops (A, B, and C) are in close proximity to each other (Fig. 3.3). Each outcrop displays decimeter- to meter-scale vertical relief along the oil-water contact (Fig. 3.6). Two-dimensional plots (Fig. 3.7) demonstrate that the bitumen-water contact is straight to undulatory, and is locally inclined. The maximum relief exhibited by the contact along any of the outcrops is 5 meters; the standard deviation along the length is +/-1.51 meters. Over the 44-meter length of outcrop C (Fig. 3.7), the contact climbs 5 meters, from the lowest to the highest point. Superimposed on this are undulations with a wavelength of

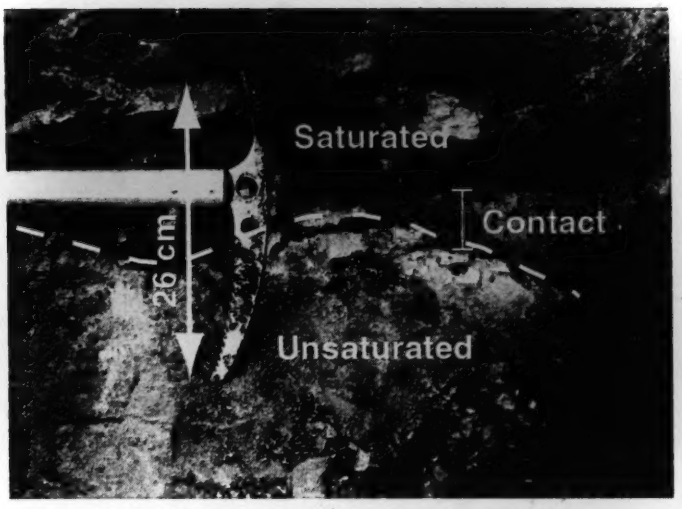


Fig. 3.5. The contact exposed in outcrop. The sharp and undulating nature can be seen clearly here.

a few meters, and amplitude up to a meter (Fig. 3.7). The smaller outcrops, A and B, (Fig. 3.7) show similar undulations.

Although the bitumen-water contact is typically sharp, there are several examples from two of the three outcrops where the contact is a patchy transition from the water-saturated sands to the bitumen-saturated sands. Patchy heterogeneity (Fig. 3.8), is manifested by encapsulated bitumen pockets that are preserved below the bitumen-water contact and, less commonly, vice versa. The size of the remnant bitumen pockets ranges from centimeter-scale to almost 2 meters in diameter. They may remain attached to the main body of the bitumen above by extension of a narrow neck or may apparently (from the outcrop face) be completely isolated within the water zone (Fig. 3.8). All the petrographic sections up to 4 meters below the contact in the McMurray Formation show thin, remnant oil envelopes on grains (Fig. 3.9) indicating the oil migrated vertically through the porous media before the terminal bitumen contact.

Detailed grain size profiles were generated along two of the outcrops. The bitumen-water contact commonly occurs close to beds characterized by the coarsest grain size but does not necessarily occur in the coarsest sediment or at a coarse-fine contact (Fig. 3.7; 3.10). Moreover, the bitumen-water contact characteristically occurs in fine- to medium-

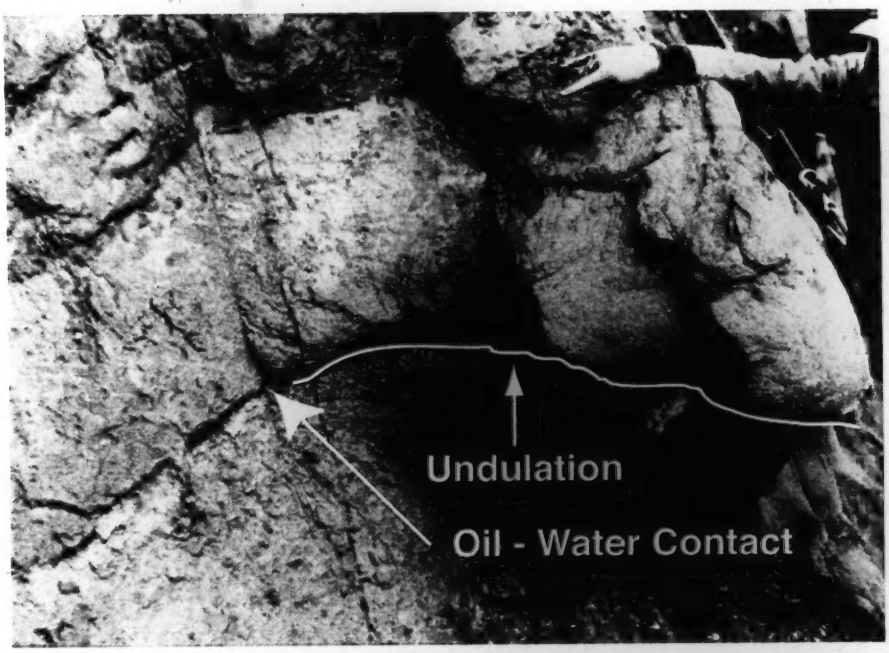


Fig. 3.6. Vertical undulation and variation at the meter-scale along the oil-water contact. The bitumen saturated zone is slightly more resistive to weathering.

grained sand, usually where the grain size increases above the interface (Fig. 3.7; 3.10).

Minor calcite cement is observed in both the bitumen- and water-saturated sediments. Locally, siderite cement is common in the water-saturated sands and up to one meter above the contact in the bitumen-saturated sand. Empirical observation indicates that across the contact, the degree of bitumen saturation and quantity of siderite cement are inversely related. The siderite is most abundant below the bitumen-water contact where it may completely occlude the pore spaces. Some remnant bitumen surrounds individual sand grains. A minimal distance above the contact, siderite is present in the smaller pores in the bitumen-saturated sand. One meter above the contact, the sediment is exclusively bitumen-saturated and no siderite is present.

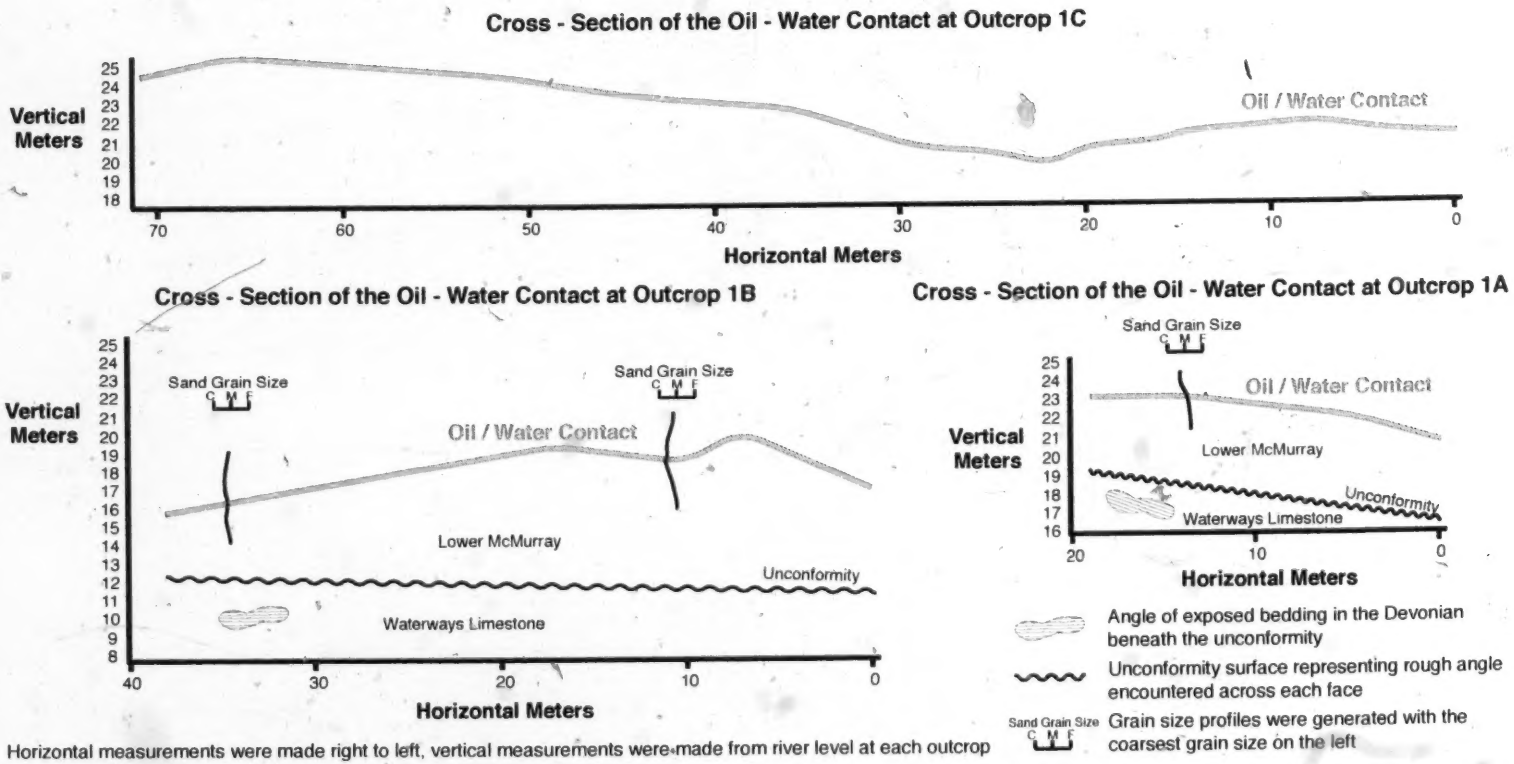


Fig. 3.7. Two-dimensional plots of the oil-water contact to scale at all three outcrops examined. Rough grain size profiles and the distance above the unconformity surface are plotted as well. At this scale of observation the implications of an undulating oil-water contact are more easily identified.

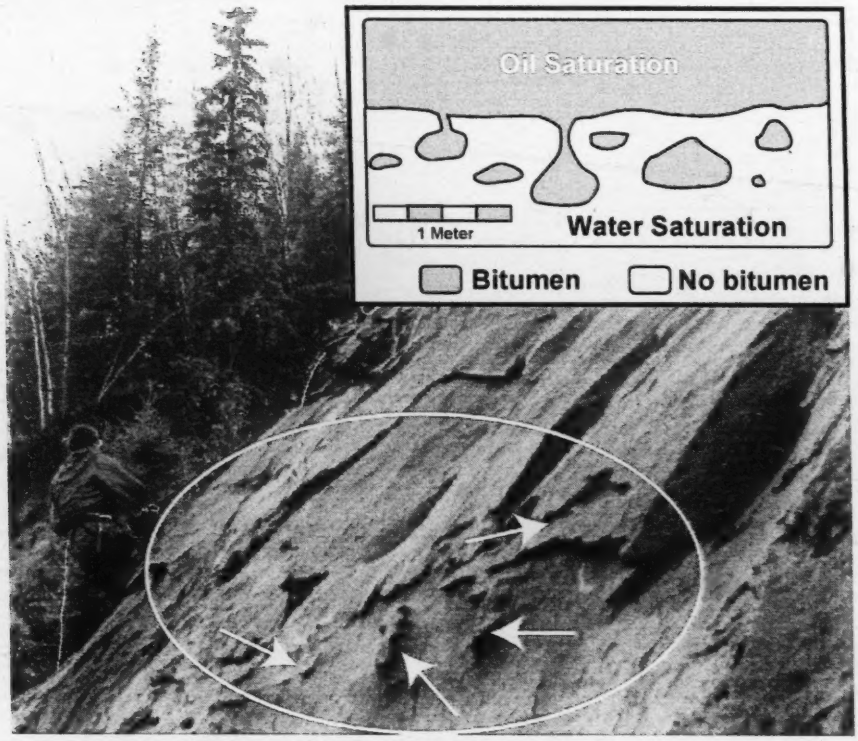
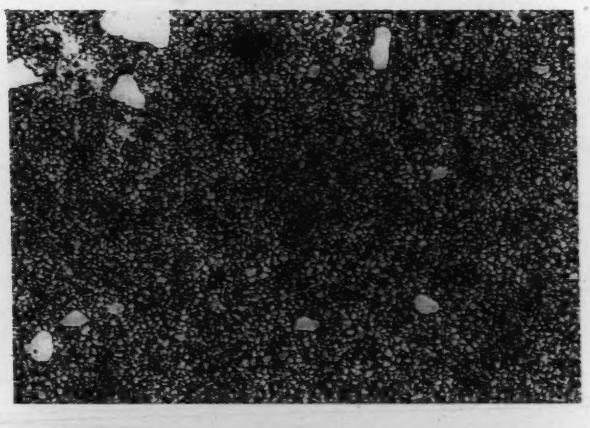


Fig. 3.8. Patchy heterogeneity observed along the face of Outcrop 1C. The more resistant pods are oil saturated while the recessed areas are water-saturated weathered sand. Inset is a schematic diagram of the heterogeneity observed below the oil-water contact

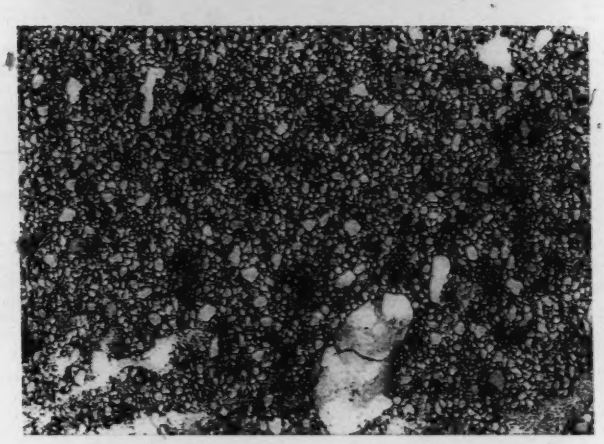
INTERPRETATION AND DISCUSSION

Core examples of the bitumen-water contact commonly do not show sideritization of the unsaturated sands. It is interpreted that the siderite observed at outcrop is a recent phenomenon related to groundwater discharge through the outcrop face. It is therefore considered unlikely that the siderite cement influenced the development of the bitumen-water contact.

The undulation and patchy heterogeneity between saturated and unsaturated sands at the contact may be attributed to several factors. One possibility is volume loss due to oil degradation. Masters (1984) noted that as oil degrades, its volume must decrease. Buoy-



A



B

C

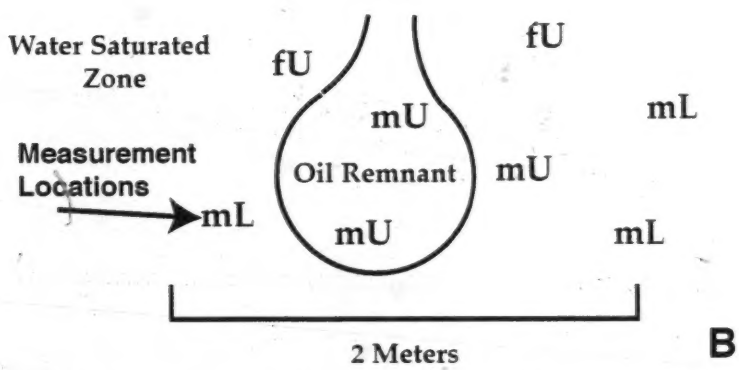
Fig. 3.9. Thin sections cut from rock taken one meter above (**A**), immediately below (**B**), and one meter below (**C**) the oil-water contact. The siderite is grey compared to the dark grey/or white sand grains and the black colored oil.

Outcrop / Depth	OC 1A	OC 1B 35m	OC 1B 11m
+ 50cm	mU	mU	mU
+ 20cm	mL	mU	mU
+ 10cm	mL	mU	mU
Contact	fU	mU	cL
- 10cm	fU	mU	mU
- 20cm	fU	mU	mL
- 50cm	fU	mU	mL

A

Patchy Heterogeneity Grain Sizes

Outcrop 1C



B

Fig. 3.10. Grain size measurements taken across the oil-water contact at random locations on all three outcrops (**A**), as well as measurements taken around an oil-saturated remnant in a patchy zone of heterogeneity beneath the oil-water contact at Outcrop 1C (**B**) (all measurements taken using the Wentworth Field Grain Size Comparison Chart).

ancy pressure would therefore cause the oil-water contact to migrate upward as the oil degraded to bitumen. Undulations may develop because the bitumen biodegrades unevenly both spatially and temporally, thereby resulting in different rates of volume loss at the scale of a few tens or hundreds of meters. Oil degradation causes a progressive increase in viscosity and increase in density, so that the oil-water contact gradually loses capacity to equilibrate to a base level. Bottom water fills the spaces relinquished by the oil due to loss of volume, explaining the staining observed in the water leg. However, remnant oil staining in the underlying water leg cannot be exclusively attributed to volume loss of the oil. Remnant staining could also be an artifact of initial migration, or, where there was an overlying gas cap, fluctuations in the hydrodynamic pressure regime of the reservoir could cause changes in gas volume and subsequent fluctuation of the elevation of the oil/water contact.

Differential degradation at the centimeter to decimeter scale may also explain the sporadic patchy nature of the bitumen-water contact. Another possibility is that during degradation, the oil increases in density faster than it loses mobility due to the increase in viscosity. Perhaps there is a point where the oil density is slightly greater than the formation water, but still mobile enough for it to sag into the water zone, with isolated portions breaking off and sinking to become isolated pockets. Athabasca bitumen in the Syncrude/Suncor area (near Steepbank River) has an API gravity of 8° to 10°. This equates to a Specific Gravity between 1 and 1.014, equal to and somewhat greater than fresh water. Shallow formation water in the Lower Cretaceous of Northeast Alberta is in the range of 10,000 to 20,000 mg/l, (Jardine, 1974; Deroo *et al*, 1977) corresponding approximately to a Specific Gravity of 1.014 to 1.007 (= 8° to 9°API gravity). Therefore the bitumen has degraded to a density approximately equal to the present-day formation water, and the isolated pockets of bitumen adjacent to the bitumen water contact may have resulted from sagging due to slight differences in density.

Capillary pressure due to grain size variations in the sediment can also be expected to

influence the nature of the bitumen-water contact. Since a sedimentary rock can be thought of as an infinite number of intergranular 'tubes', the position of an oil-water contact reflects the statistical average of the pore throat diameters in the reservoir. Even monolithologic reservoir facies will typically contain grain size variations within facies and across facies boundaries. Any change in grain size will affect the capillary pressures in the reservoir. Empirical observation suggests that the patchy and undulatory nature of the bitumen-water contact at the Steepbank outcrops has some relationship to grain size.

Hubbert (1953) noted that under capillary forces alone, oil will move in the direction of increasing grain size. Lerche and Thomsen (1994) state that in a monolithologic aquifer, in which grain size varies with position along an aquifer, capillary pressure will drive oil preferentially into the largest pores, and retard passage into less porous, less permeable regions. In the patchy zones of the bitumen-water contact, the grain size is finer laterally indicating a smaller pore throat size. It is into this smaller pore throat size that water migrates to replace the oil in that particular location.

The isolated pockets of oil and water most likely develop due to slight decreases in grain size both laterally and vertically, trapping the continually degrading bitumen as the longer chain hydrocarbon molecules become too large and viscous to migrate through a decreased pore throat size. These factors lead to sealing conditions (Lerche and Thomsen, 1994). Figure 3.8 shows how this appears at outcrop scale.

APPLICATIONS TO RESERVOIR CALCULATION

Analysis of the bitumen-water contact shows that it is undulatory, and to a degree, unpredictable. Given the average standard deviation relief of 1.51 meters, a volumetric calculation has a potential error of 4,218,989 m3 (but significant only to 4.22 x 106) over a section of land or 15,100 m3 over a hectare. Assuming an average porosity of 34% and an average bitumen saturation of 85%, then the bitumen proportion of the total volume is

4,200,000m3 X .34 X .85; equal to approximately 1,200,000 m3 (7.6 million bbls) per section or 15,100m3 X .34 X .85; equal to 4364m3 per hectare. This is a substantial amount of bitumen, and in a thin reservoir such uncertainty might be considered unacceptable.

An undulating oil-water contact may also have implications regarding mine wall expansion or in-situ recovery. As previously stated, the best reservoir sands typically occur in the lower to middle McMurray just above the bitumen-water contact. Where planning a mine wall expansion, the contact must be considered as it may influence bitumen-in-place calculations as well as the decision on which wall to expand for best potential lateral extent and ore thickness. A water leg must be drawn down in order to recover deeper ore at the bitumen-water contact without risk of flooding or swamping the extraction pit. Failure to pump the water level below the deepest ore risks leaving it behind, or at best would require remedial pumping operations.

Mapping the bitumen-water contact in the subsurface without proper consideration of the potential errors due to the undulation could generate problems. One of the main difficulties with mapping from drillhole data is that the horizons are observed as a point and not a plane. Interpolating between two drillholes as shown in figure 9 could prove problematic for an in-situ recovery scheme if the production well is placed close to the basal aquifer. Even if the recovery well is perforated at some normally acceptable vertical distance from the water zone, the original bitumen-water contact may rise 5 meters or more within a short (<50m) lateral distance from the bottom-hole location of the well. This could cause unexpected water coning after only a short time. An irregular bitumen-water contact may be especially problematic in SAGD projects where recovery wells run horizontally near the base of the reservoir. There is a risk in running a long horizontal production well through an elevated area of the bitumen-water contact, and therefore producing excessive formation water. Since the lower production well is initially used for steam injection when bringing a well pair on production, the proximity or penetration of the bitumen-water contact may cause a breach of the steam chamber into the bottom water zone, resulting in severe

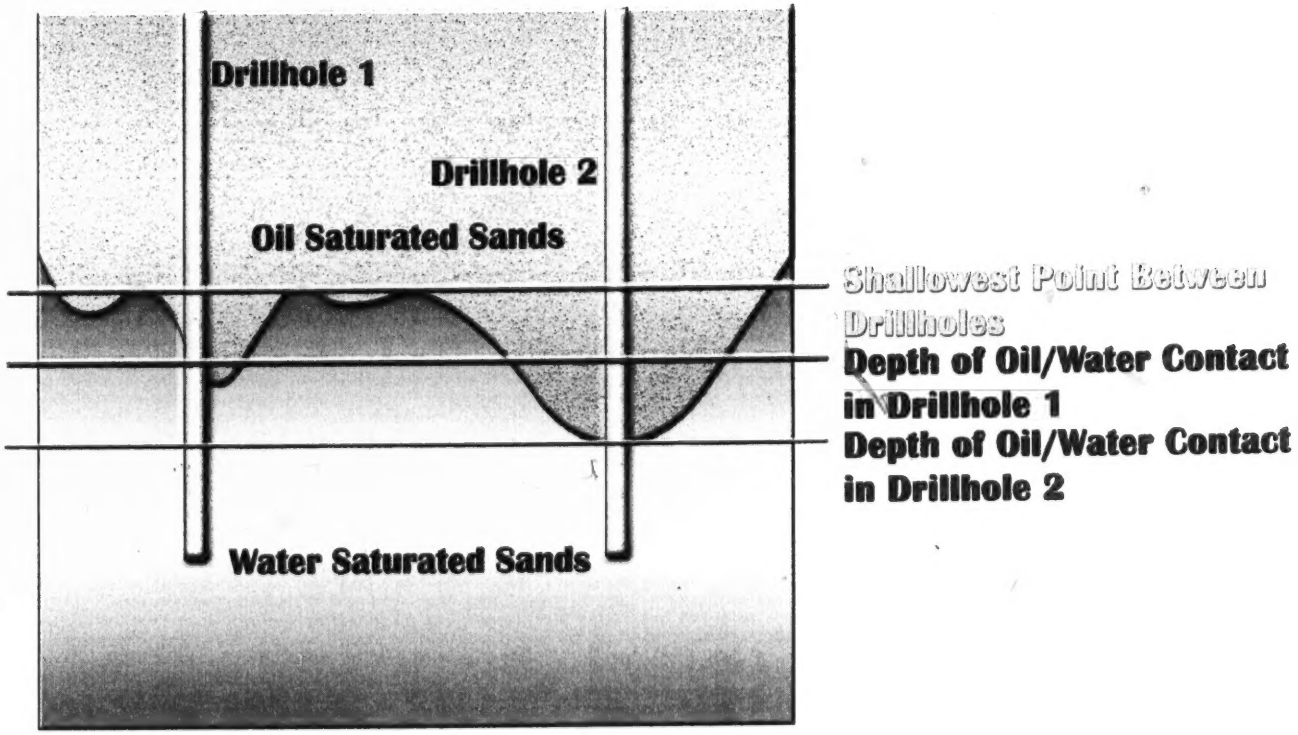


Fig. 3.11. Schematic diagram and explanation of the effects of the oil-water contact on reservoir mapping and in-situ production planning.

thermal energy loss.

CONCLUSIONS

This paper introduces a novel method of measuring the topography of a surface in outcrop using a hydrostatic level. This methodology permitted the documentation of several significant characteristics of the frozen bitumen-water contact of the Athabasca Oil Sands. Analysis of data gathered from the Steepbank River outcrops demonstrates the variable nature of the bitumen-water contact. Not only does the contact undulate, but it also undulates at a scale relevant to both reserves calculation and mine-wall or production borehole placement. The amplitude of these undulations observed in the three outcrops ranges from 2 to 5 meters over an outcrop length of 20 to 70 meters. The morphology of the contact is not strictly controlled by sedimentary facies or local stratigraphic surfaces, and the location and geometry of the contact could not be reliably predicted at this scale. However, several factors appear to have influenced the contact during and after oil migration.

We hypothesize that the undulation and heterogeneity of the bitumen-water contact may be attributed to the interaction of several features or processes. These include: grain size, oil degradation history, and gas-cap pressure history. Sediment grain size appears to be the primary physical feature of the reservoir that has affected the bitumen-water contact, since it would have influenced both the hydrodynamic flow regime and degradation process. Intervals of coarser and finer grain size would have distorted the oil-water contact during migration and trapping due to differential migration of oil driven by capillary pressure.

Volume loss due to oil degradation may also have affected the bitumen-water contact. Undulations may develop because the bitumen biodegrades unevenly, resulting in different rates of volume loss at the scale of a few tens or hundreds of meters. The associated increase in density and viscosity would immobilize the oil, preventing the basal contact

from reaching an equilibrium base level, and resulting in the undulations and perhaps patchy heterogeneity on a smaller scale. The increase in density due to degradation may also contribute to patchy heterogeneity. When the bitumen density approaches the density of the formation water, it may still retain enough mobility to sag into the basal water leg.

With the presence of an overlying gas cap, fluctuations in the hydrodynamic pressure regime of the reservoir could cause changes in gas volume and subsequent fluctuation of the elevation of the oil/water contact. Gas caps are common in cores in the surrounding area but there is no current method of back-calculating the pressure changes over time in these zones.

Failure to account for the undulatory nature of the basal bitumen-water contact in the Athabasca Oil Sands may have important economic consequences. The variability noted herein should therefore be recognized as a potential source of error associated with reserves calculations, production well placement and mine planning.

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CHAPTER 4 - SUMMARY AND CONCLUSIONS

This thesis has sought to evaluate the sedimentary nature and resource character of the McMurray Formation in the surface-mineable portion of the Athabasca Oil Sands. As one of the largest sources of hydrocarbons in the world, understanding of its integral facies relationships is paramount to successful exploitation. Facies definition and facies association relationships in a stratigraphic framework are an effective way to reconstruct this complex depositional regime. The nature of the oil in this reservoir is also complex due to the range and degree of degradation that has occurred. The observance and analysis of an oil-water contact along the banks of the Steepbank River has provided a unique opportunity to quantify the character of an oil-water contact in a scale rarely observed.

Chapter II examined the sedimentary character of the McMurray Formation in outcrop and core to develop a predictive stratigraphic model. The rarely described outcrops along the Ells River combined with the enormous amount of recently obtained core by Canadian Natural Resources Ltd. for their bitumen mine provided an opportunity to unite fresh core and well-exposed outcrops in a genetic stratigraphic model. The definition of facies and facies associations in the study area required an integrated approach involving sedimentological, ichnological, and stratigraphic analysis. The identification of 18 individual facies that comprise six facies associations provided a framework to analyze the McMurray Formation in a genetic stratigraphic context. From this, it was recognized that the McMurray Formation was deposited in an overall transgressive cycle with fluvial deposits at the base passing vertically into estuarine sediments.

Sediments exposed along the Ells River reveal a history beginning with creation of a paleovalley in exposed Devonian strata through a combination of subsurface evaporite dissolution and fluvial erosion. This basal surface is defined as a Lowstand Surface of Erosion (LSE) and marks the initiation of McMurray Formation deposition. Sediment in Facies Association 1 of the McMurray Formation records deposition in a braided fluvial

system confined to lows in the paleovalley unconformity. The strata here shows no physical or biological structures indicative of marine influence.

Facies Association 2 preserved near the Ells River records deposition in a meandering fluvial system that is exposed to increased tidal effects and salinity levels upsection. This facies association continued to fill the paleovalleys in broader lows and is oftentimes seen to immediately onlap and overly the unconformity. The development of Inclined Heterolithic Stratification (IHS) as defined by Thomas *et al.*, (1987) indicates the influence of tides associated with the development of a tide-influenced estuary. The rare occurrence of trace fossils associated with brackish water conditions that increase upwards indicates the increased proximity to higher salinities and tidal influence (ie. continued transgression)(Gingras, 1999).

Facies Association 3 represents flood basin deposition on floodplains developed above the meandering system of Facies Association 2. The appearance of muddy zones that have been oxidized from exposure and the development of coal beds indicate subaerial sedimentation. Trace fossils are limited in this environment due to the harsh conditions associated with deposition away from marine conditions (Bromley, 1990).

Facies Association 4 reflects sedimentation in a meandering, tidally-influenced fluvial system that has experienced increasingly brackish water conditions. The prolific trace fossils from both the *Cruziana* and *Skolithos* ichnofacies that develop in monospecific assemblages give evidence that these sediments were deposited in an upper- to middle-estuary setting (Wightman and Pemberton, 1997). Well-developed IHS indicate strong tidal effects in this association.

Facies Association 5 is characterized as sand- to mud-dominated tidal flats that display a similar ichnological signature to sediments found in Facies Association 4. The occurrence of tidal flats as the topographically higher component of tidal point bars helps explain the interfingering relationship between Facies Associations 4 and 5. The upper contact of Facies Association 5 is identified as a Tidal Ravinement Surface (TR1) that

separates inner to middle estuary sediments from outer estuary sediments. This surface is traceable through every outcrop and core that expose Facies Associations 5 and 6 but is not considered an isochronological surface.

Facies Association 6 is composed of three facies that represent sedimentation in the outer reaches of the estuary. A bay fill cut by sand bodies is identified to have existed towards the end of McMurray time. The trace fossils in Facies Association 6 are much more numerous while individual traces develop increased size and represent more complex behaviors. This signals true brackish conditions where environmental conditions allowed for more organisms to colonize the substrate. This association also signals a shift from sedimentation controlled by fluvial and tidal processes to an environment controlled by wave and tidal processes. The upper contact of the McMurray Formation near the Ells River is manifested as a Wave Ravinement Surface (WR1) that separates the outer estuary sediments of Facies Association 6 with the fully marine shoreface sediments of the Wabiskaw member of the Clearwater Formation.

Chapter III attempts to quantify an oil-water contact exposed in three-dimensions along outcrops of the Steepbank River using a novel measurement technique. The contact suggests that the oil and water found in the McMurray Formation initially resided in a standard density controlled hydrologic relationship where oil floated atop the water in the reservoir. Biodegradation of the oil has since caused volume loss to occur that has not been uniform along the contact. As such, undulation and patchy heterogeneity have developed along this surface. Capillary pressure has also been an influence in the current placement of the oil-water contact as lateral local facies variability is high. It is also proposed that the presence of a pressurized gas cap that is no longer identified may have affected the nature of the contact.

The McMurray Formation contains a complex array of facies that can be arranged into mappable and independent facies associations. These associations also allow identification of distinct, genetically defined stratigraphic surfaces that occur within the strata.

Integrating sedimentology, stratigraphy, and ichnology can provide a framework to aid in the understanding of these deposits. Enhanced understanding of the behavior of the petroleum resources trapped within this reservoir will assist and promote the effective and responsible exploitation of this resource.

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